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Assessment and Conceptual Design of Photovoltaic Hybrid Systems

Engineering and Economics Research, Inc.
Office of Kenneth W. Cobb, Consulting Engineers, P. A.
and
National Rural Electric Cooperative Association

October 1983

Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATIC
Lewis Research Center
Under Contract DEN3-299

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Division of Photovoltaic Energy Systems

NOTICE

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Washington, D. C. 20036

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1.0 INTRODUCTION

1.1 Need for the Study

In the decision to deploy terrestrial stand-alone power systems, the cost and availability of energy produced are two important but conflicting considerations. The increased cost for site visits to resupply and service conventional electric generator systems has become a significant factor in the cost-availability trade-offs which must be made when considering these systems for use in stand-alone applications. In many cases, the cost of the energy provided is prohibitive for the application, and availability goals must be compromised. Similarly, the cost of a renewable energy system (e.g., photovoltaic (PV), wind-turbine and hydroelectric) is often prohibitive because of the large energy storage capacity needed to sustain system availability during diurnal and seasonal variations of these energy sources. The high cost of energy storage is a dominant factor in stand-alone renewable energy system cost and, like fuel costs, does not appear amenable to reduction in the near future.

One way to reduce the cost of energy systems without degrading availability is to reduce the need for large fuel supplies and/or storage capacities by utilizing a combination of several power sources (called a hybrid power system). In a PV hybrid system, a PV power subsystem is combined with other non-PV power subsystems to match the load demand in a most cost-effective way.

The underlying assumption of the hybrid concept is that a desired availability can be attained at lower life cycle cost than that of either a conventional or a single source renewable energy system. Recently there has been considerable interest in developing hybrid power systems for use in remote locations.[1] However, because of the diversity of possible systems, a comprehensive and systematic assessment of PV hybrid systems for stand-alone applications has not been undertaken up to this point.

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1 For example see: Calzolari, P.U. et al., "The Photovoltaic - Aeolian Plant at Passo Mandrioli (Italy)," Revue Internatione D'Heliotechnique, 1980; Castle, J.A., et al., "Analysis of Merits of Hybrid Wind/Photovoltaic Concept for Stand-Alone Systems", Hughes Aircraft Company; Colin, M.R., "La Station D'Energie Type Aerosolec," Centre National d'Etudes des Telecommunications, Issy-Les-Monlineaux; Crisp J.M. et al., "Analysis of Remote Site Energy Storage and Generation Systems," AFAPL-TR 79-2056, Air Force Aero Propulsion Laboratory, Wright Patterson AFB, Ohio, July 1979; DAF Indal Limited, "Wind Turbine Assisted Diesel Generator Systems," Mississauga, Canada; French, R.L. and K.T. Miller, "Concepts for Small-Scale Hybrid Solar-Hydroelectric Power Plants," Waterpower 79 International Conference, October 1979; Modern Power Systems, "Hybrid Wind/Solar System Developed," July 1982; (continued on next page)

1.2 Objectives of the Study

This study is designed to provide the first comprehensive assessment of the potential for PV hybrid systems for stand-alone applications in the 5 to 10 year time frame. The applications under consideration have energy demand levels ranging from 10 to 1000 kWh/day. It will achieve this objective by:

1. Surveying and examining a number of PV hybrid systems concepts (such as PV hybridized with conventionally fueled engine-generator sets, wind energy conversion systems, small hydro, fuel cells, wave power generators, organic Rankine cycle generators and Stirling engines);

2. Determining appropriate PV-hybrid system technologies (based upon an evaluation of the technical and economic merits as well as user acceptability);

3. Selecting, conceptually designing, and analyzing several promising stand-alone PV-hybrid systems for mid-term (5-10 years) electric power applications.

A systematic evaluation of PV hybrid systems conducted in this manner will identify areas where R&D and additional information is required. It will also provide industry with information needed to design optimal PV hybrid systems with attractive sales potential. The study activities have been organized into four technical tasks and one reporting task as outlined below:

- Task I - Definition of Candidate PV Hybrid Concepts

  The purpose of this task is to identify and characterize PV hybrid systems that have the potential of providing economically competitive electrical energy in the range of 10 to 1000 kWh/day.

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1 (continued from previous page) Munjal, P.K., "Evaluations of Breakeven Photovoltaic Module Costs for Village Power," The Aerospace Corporation, August 1982; Nasser, A.E.M., "Utilization of Wind/Solar Energy in Generating Electricity in Saudi Arabia," Riyadh University, Saudi Arabia, 1981; Norton Jr., J.H. and N.S. Christopher, "Hybrid/Wind Closed Cycle Vapor Turbogenerator Power System," IEEE, 1982; Payne, P.E. and J.L. Sheehan, "Hybrid Alternate Energy System," American Chemical Society, 1979; Powell, W.R. et al., "Alternate Hybrid Power Sources for Remote Site Applications," Report No. CG-D-06-81, U.S. Coast Guard, February 1981; Solar Energy Digest, "You Can Now Have An All-Electric Solar Home for A$25,000 with this Solar Cell/Wind Turbine Hybrid System," Volume 15, No. 4, October 1980; and Young, S.K., "Integrated Solar Energy System Optimization," Transactions of the ASME, Volume 104 November 1982.

- <u>Task II - Analysis and Screening of PV Hybrid System Concepts</u>

  The principal purpose of this task is to conduct a detailed evaluation of several high potential hybrid systems identified in Task I and select four for detailed conceptual design. To achieve task objectives, a computerized PV hybrid system simulation and costing model will be developed. The model will permit analyzing the performance of each system over a broad range of energy demand, resource conditions and other parameters. This task will also evaluate worldwide resource availability and the appropriateness of institutional, cultural, economic and social environments worldwide for widespread dissemination of PV hybrid systems.

- <u>Task III - Conceptual Design of Hybrid Systems</u>

  The purpose of this task is to perform detailed conceptual designs of the four PV hybrid systems selected during Task II.

- <u>Task IV - Development Program Recommendations</u>

  The purpose of this task is to recommend a development program for public and private sector involvement that will permit implementation of PV hybrid systems within a 5 to 10 year time frame.

- <u>Task V - Reporting Requirements</u>

  The purpose of this task is to ensure adequate technical and financial information transmission to NASA.

The purpose of this final report is to document the work done and conclusions reached during this study.

1.3 Final Report Organization

Section 2.0 documents the procedures used and the conclusions reached in defining potentially valuable PV hybrid systems. Section 3.0 provides an overview of the computer models used to size, cost and simulate the performance of the PV hybrid systems. It also demonstrates how the models are to be used. Section 4.0 shows the results of PV hybrid systems analysis. This section discusses the major implications of the analyses and recommends four systems for detailed conceptual design. Section 5.0 employs the simulation models to determine the optimal configurations of the four hybrid system for a NASA-specified set of resource conditions and demand profiles. In this Section redundancy requirements to account for equipment unreliability are also discussed. In addition, the effect of demand uncertainties on the design is investigated. Section 6.0 describes the detailed conceptual designs, their operation, cost and maintenance requirements. Section 7.0 documents the additional development work needed to improve the cost, reliability and performance of the hybrid systems. Appendix A lists the data used for the Section 4.0 analyses and Appendix B contains source code listings of the simulation models.

2.0 PROPOSED PV HYBRID SYSTEMS

The purpose of this section is to describe the criteria and procedures used to select PV hybrid systems for more detailed evaluation. The eight systems selected for preliminary evaluation are the following:

- PV/wind energy conversion systems
- PV/hydroelectric power
- PV/wave power
- PV/diesel generator
- PV/gasoline generator
- PV/fuel cell
- PV/CCVT (close cycle vapor turbogenerator)
- PV/Stirling engine generator

2.1 System Description

The proposed PV hybrid systems will have the generalized configuration shown in Exhibit 2-1. The power system will be able to supply the load directly from the PV array, the alternative power source and/or the battery. The batteries can be charged by the PV array as well as the alternative power source. Smaller systems (less than 5 kW) will have simpler configurations and equipment. For example, a peak power tracker is not used and the loads are supplied with direct current (DC) power. In large systems (greater than 5 kW), a sophisticated, high efficiency inverter can be used, along with a peak-power tracker, so that the loads are supplied alternating current (AC). Multiple voltages are also more likely in the large system, therefore AC power would appear to be preferable.

The PV hybrid system must be capable of the following characteristics:

- Provide electrical energy (AC or DC) in the approximate range of 10 to 1000 kWh/day.
- Be capable of domestic and international applicability and have a potential for low cost replication.
- Serve a variety of electrical loads.
- Have an operational availability of 80-99%.

- Be a viable alternative to extension of utility grids to remotely located applications, such as residential clusters, villages and water desalination plants.
- Have subsystems which are modular and may be distributed in location.
- Have the ability to be connected together to form a network.

The hybrid systems being considered have the following possible electrical energy generator/supply characteristics:

- DC power generated/DC power supplied
- DC power generated/AC power supplied
- DC and AC power generated/AC power supplied

The major components of the hybrid system selected for preliminary evaluation are outlined below:

- PV/wind energy conversion systems

  The major components of this system are: (i) PV array, (ii) Wind turbine generator (horizontal or vertical axis), (iii) Battery, (iv) Balance of system (controllers, power conditioners, etc.). Both generators can supply the load and charge the batteries.

- PV/hydroelectric power

  The major components are: (i) PV array, (ii) Hydroelectric turbine generator, (iii) Battery, (iv) Balance of system. The hydro turbine can be a reaction or impulse type depending on the hydraulic head. Since the hydroturbine will have to operate under a range of flow conditions, crossflow turbines may be preferred since they have high efficiency from 10% to 110% of rated flow rate.

- PV/wave power

  The major components are: (i) PV array, (ii) Mechanical device able to extract energy from wave motion, (iii) Battery, (iv) Balance of system.

- PV/diesel and gasoline generator

  The major components are: (i) PV array, (ii) Diesel or gasoline powered generator, (iii) Battery, (iv) Balance of system. The use of the battery is optional. It depends on the operating protocol and the cost trade-offs between battery and fuel consumption.

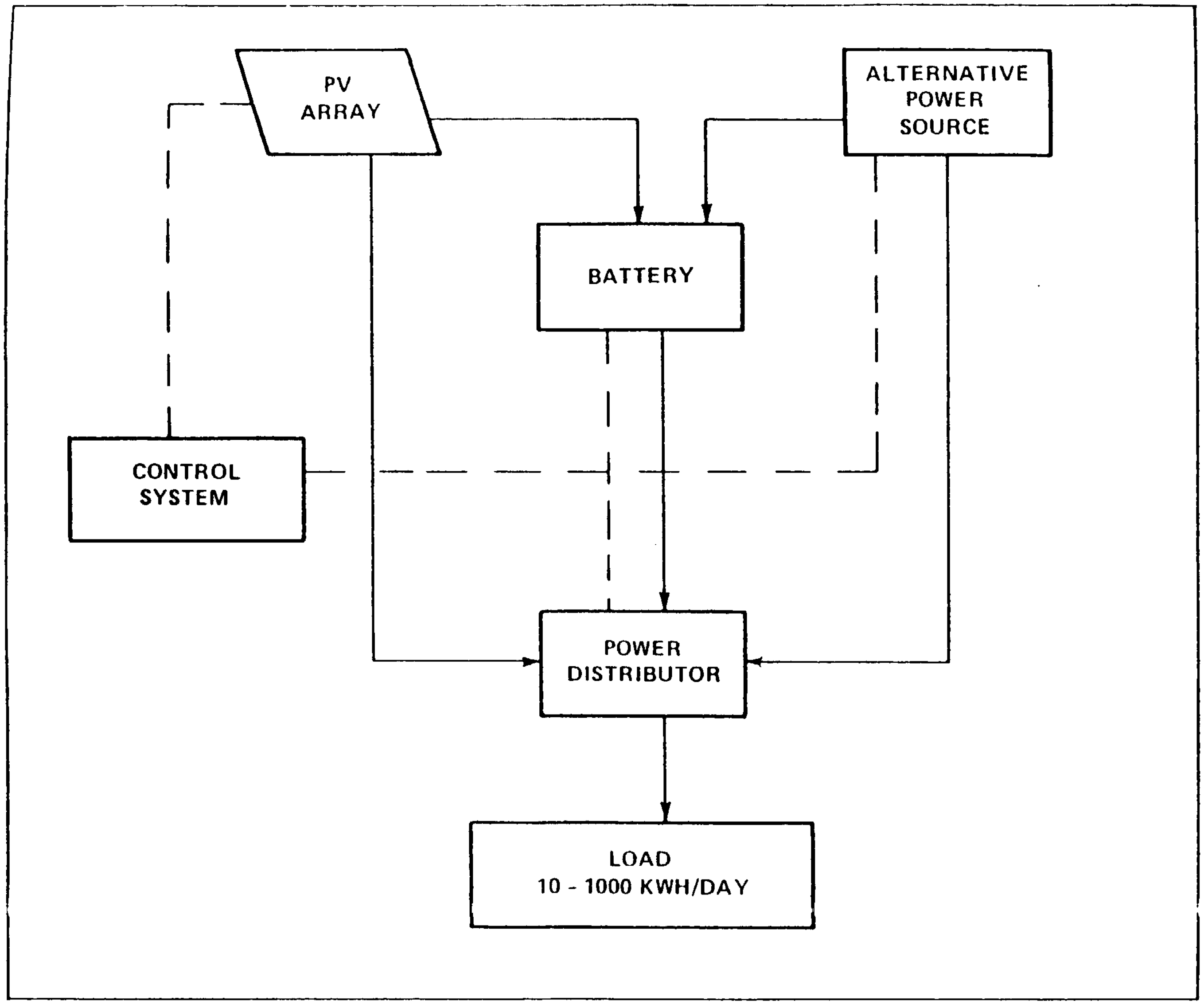


EXHIBIT 2-1: GENERALIZED PV HYBRID CONFIGURATION

- PV/fuel cell

  The major components are: (i) PV array, (ii) Fuel cell, (iii) Battery, (iv) Balance of system. Due to near-term availability, a phosphoric acid fuel cell will be used.

- PV/CCVT (Closed cycle vapor turbogenerator)

  The major components are: (i) PV array, (ii) CCVT generator, (iii) Battery, (iv) Balance of system. The CCVT can use fuels such as LPG, kerosene, jet fuel, diesel, and alcohol. Preferred fuel is LPG.

- PV/Stirling engine generator

  The major components are: (i) PV array, (ii) Stirling engine generator, (iii) Battery, (iv) Balance of system. The principal reason for considering this hybrid system was the multifuel capability of the Stirling engine.

2.2 System Selection

PV hybrid systems were evaluated using a formal evaluation procedure to select those systems that warrant a more detailed assessment. In the evaluation procedure each hybrid system was ranked using four independent criteria, and assigned a final overall ordinal ranking. An overview of the selection process is shown in Exhibit 2-2.

2.3 Selection Criteria

To select the subset of most promising hybrid systems worthy of a more detailed analysis, each system was ordinally ranked against four major criteria:

- Availability is defined as commercial availability of 1-100kW systems in the next 5-10 years. Since the PV hybrid systems are planned to be used in the next 5 to 10 years, the technology for the proposed system must be commercially available in this time frame. It is also preferable if the system components have already been developed and tested, since this will help reduce cost, increase reliability and improve acceptability.

- Cost is defined as ability of the hybrid system to provide reliable power for stand-alone applications at a competitive price. The subcriteria used in the preliminary evaluation of cost criteria are:

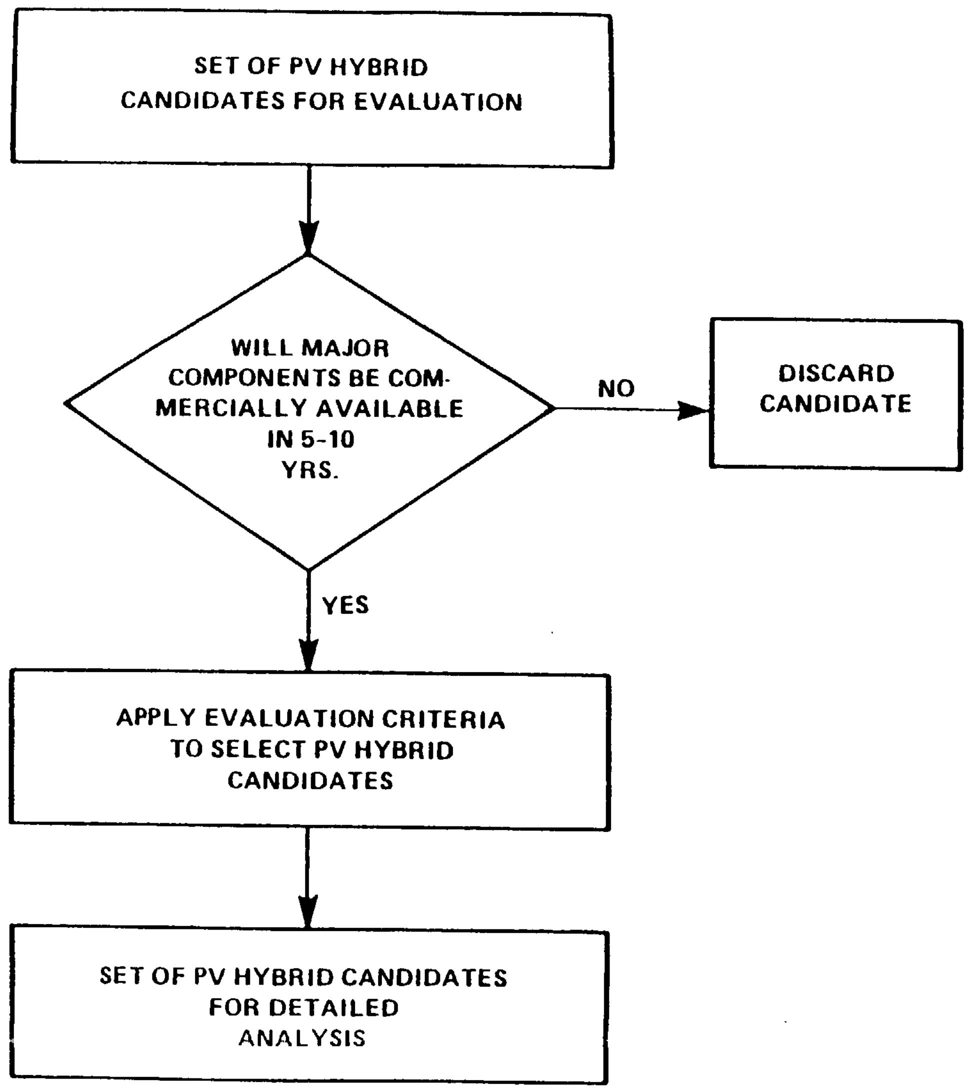


EXHIBIT 2-2: SELECTION PROCESS FLOW DIAGRAM

- Capital cost
- Fuel cost
- O&M cost
- Reliability
- Life

PV hybrid systems, in order to be feasible, must be cost competitive with the traditional power systems. This is a major reason for using a PV hybrid system. Three of the proposed systems, PV/wind, PV/hydro, PV/wave, have zero fuel costs; so even if their capital cost is higher than a conventional system, over the system life they may be more cost-effective. Operation and maintenance cost is also an important factor determining a system's cost competitiveness. The reliability and life of the system are factors determining cost; since lower reliability implies greater O&M needs and shorter life means more frequent replacement. The evaluation also considered the potential for cost reduction.

- Applicability is defined as the ability of the hybrid system to have widespread applicability worldwide. The subcriteria used in evaluating the applicability of a system were:

  - Resource availability
  - Extent of potential use
  - Responsiveness to a variety of demand conditions
  - Suitability of existing institutions/infrastructures for utilizing hybrid systems.

  Resource availability is a measure of the extent of locations worldwide where insolation and other resources needed to operate the alternative power source are available in adequate quantities to ensure high plant capacity factors. Locations where insolation availability and alternative resource availability are highly complementary are especially suitable for the hybrid system. The extent of potential use is a measure of the demand for systems. The responsiveness of the system measures its ability to satisfy time-varying demand for electric power. Finally, those hybrid systems were ranked highly that can use existing institutions/infrastructures to produce, install, maintain, finance and use such systems.

- Acceptability is defined as the ability of the hybrid system to generate power safely and with minimal environmental damage. The subcriteria used were:

  - Safety
  - Environmental impact

Each hybrid system was subjectively evaluated on an ordinal scale against each of the criteria. Exhibits 2-3 to 2-6 illustrate the ranking process and the reasoning behind the rankings. The overall ranking is shown in Exhibit 2-7. Systems such as PV/diesel and PV/hydro have high ranking because they use known technology,

EXHIBIT 2-3

COMMERCIAL AVAILABILITY OF SYSTEMS 1-100KW IN SIZE IN 5-10 YEARS

HYBRID CANDIDATES	STATUS	RANK
1. WIND	STANDALONE SYSTEMS CURRENTLY AVAILABLE, GAINING ACCEPTANCE WORLDWIDE AS A FEASIBLE POWER SOURCE.	4
2. HYDRO	WIDESPREAD USE WORLDWIDE	2
3. WAVE POWER	WIDESPREAD COMMERCIAL AVAILABILITY APPEARS UNLIKELY IN TIMEFRAME SINCE TECHNOLOGY IS CURRENTLY UNDERGOING RESEARCH AND DEVELOPMENT.	7
4. DIESEL, GASOLINE	WIDESPREAD USE WORLDWIDE.	1
5. CLOSED CYCLE VAPOR TURBO-GENERATORS (CCVT)	CURRENTLY USED IN 45 COUNTRIES FOR 200W-5KW APPLICATIONS REQUIRING ULTRAHIGH RELIABILITY.	3
6. FUEL CELLS	WORLDWIDE AVAILABILITY MARGINAL. TECHNOLOGY IS CURRENTLY IN DEVELOPMENT, TESTING AND EVALUATION PHASE. RURAL ELECTRIC UTILITIES IN U.S. WILL INSTALL AND TEST 40KW UNIT SOON. MILITARY IS DEVELOPING A STANDALONE 40KW UNIT.	5
7. STIRLING	COMMERCIAL DEVELOPMENT HAS REACHED PROTOTYPE STAGE. GENSETS FOR MOBILE HOMES AND OTHER SIMILAR APPLICATIONS BEING OFFERED.	6

EXHIBIT 2-4

COST FACTORS

HYBRID CANDIDATES	CAPITAL COSTS	FUEL COSTS	O&M COSTS	RELIABILITY	LIFE	RANK
1. WIND	\$1500-7000/KW, CAPACITY FACTORS $\approx$ 0.3, BATTERIES REQUIRED	NONE	LOW 1-2 PERCENT OF CAPITAL COST PER YEAR	5-15 PERCENT OF TIME FOR UNSCHEDULED OUTAGES	20 YEARS	3
2. HYDRO	\$2000-4000/KW, HIGH CAPACITY FACTORS, NO BATTERY REQUIRED, SMALL UNITS HAVE TO BE CUSTOM MADE	NONE	LOW, ABOUT 4 PERCENT OF CAPITAL COSTS	HIGH	40 YEARS	1
3. WAVE POWER	CURRENTLY COSTS IN \$4000-13,000/KW RANGE HAVE BEEN REPORTED, BATTERY NEEDED	NONE	COULD BE HIGH, SINCE LARGE UNITS WILL HAVE TO BE REPAIRED IN HOSTILE ENVIRONMENTS	INADEQUATE DATA, COULD BE LOW DUE TO HOSTILE ENVIRONMENT	INADEQUATE OPERATIONAL DATA BUT EXPECTED TO BE COMPARABLE TO HYDROPOWER PLANTS	7
4. DIESEL, GASOLINE	\$400-1000/KW, HIGH CAPACITY FACTORS, NO BATTERY REQUIREMENTS	EFFICIENCY IS ABOUT 30% FOR LARGER UNITS AT HIGH LOAD FACTORS. GASOLINE ENGINES-ABOUT 10% AT LOW LOAD FACTORS	HIGH, DEPENDS ON USAGE, POSSIBLY COMPARABLE TO CAPITAL COST EVERY YEAR	MODERATE - 2500-4000 HOURS MTBF (2-3 OUTAGES PER YEAR)	10 TO 15 YEARS	2
5. CCVT	\$13,000-90,000/KW, VERY HIGH CAPACITY FACTORS, NO BATTERY REQUIREMENTS	VERY HIGH, SINCE EFFICIENCY IS ONLY 5-7%	VERY LOW, ONE DAY PER YEAR, NO MATERIAL REQUIREMENTS	ULTRA HIGH RELIABILITY. MTBF IS OVER 20,000 HOURS	20 YEARS	6
6. FUEL CELLS	\$1000-2000/KW FOR ELECTRICITY PRODUCTION, HIGH CAPACITY FACTORS, NO BATTERY REQUIREMENTS	OVERALL EFFICIENCY ABOUT 30-40%, HIGH PART LOAD EFFICIENCIES	MINIMAL MAINTENANCE COSTS	INADEQUATE OPERATIONAL DATA, BUT RELIABILITY EXPECTED TO BE HIGH	5 YEARS	4
7. STIRLING	\$530-2600/KW, HIGH CAPACITY FACTORS, NO BATTERY REQUIREMENTS	PROTOTYPE EFFICIENCY IN THE RANGE OF 32%. LOWER IF BIOMASS FUEL IS USED. MULTIFUEL CAPABILITY	LOWER THAN DIESELS (1/2-1/3 OF DIESEL O&M)	EXPECTED TO BE HIGH, DUE TO THE USE OF EXTERNAL COMBUSTION SYSTEM	15 TO 20 YEARS EXPECTED	5

EXHIBIT 2-5

APPLICABILITY FACTORS

HYBRID CANDIDATES	RESOURCE AVAILABILITY	EXTENT OF USES	SYSTEM RESPONSIVENESS	INSTITUTIONAL INFRASTRUCTURE SUITABILITY	RANK
1. WIND	MANY COUNTRIES HAVE GOOD RESOURCES. HOWEVER COMPLEMENTARITY WITH INSOLATION NOT EXTENSIVE	VERSATILE, SINCE SYSTEMS IN THE 1-100 KW ARE AVAILABLE. ECONOMIES OF SCALE ARE HIGH IN 1-25 KW SIZE RANGE	POOR, SINCE POWER OUTPUT DEPENDS ON A HIGHLY VARIABLE ENERGY SOURCE	CONSIDERED A NEW POWER SOURCE, NOT FULLY PROVEN. THEREFORE SUITABILITY IS PRESENTLY INADEQUATE. SHOULD IMPROVE IN 5-10 YEARS	5
2. HYDRO	GOOD RESOURCES IN MANY COUNTRIES. MOST SMALL UNITS REQUIRE HIGH HEADS. BUT HYBRID SYSTEMS VIABLE ONLY WHEN THERE ARE EXTENDED LOW FLOW PERIODS	PREFERENCE IS TOWARDS LARGER SYSTEMS DUE TO GOOD ECONOMIES OF SCALE IN 5-100 KW RANGE	GOOD, SHOULD SEE FURTHER IMPROVEMENTS WITH NEW ELECTRONIC CONTROLLERS	EXCELLENT ACCEPTANCE WORLDWIDE. THERE MAY BE RESISTANCE TO RESERVOIR SYSTEMS DUE TO LAND SUBMERGENCE	2
3. WAVE POWER	GOOD RESOURCES MAINLY FOUND BEYOND 30°N AND 30°S EXCEPT WEST COAST OF AFRICA 0-20°N LATITUDE, COASTAL RESOURCE	MAINLY SMALL SYSTEMS. DUE TO ECONOMIES, LARGE SYSTEMS WILL PROBABLY BE INSTALLED BEYOND 30°N AND 30°S	POOR, SINCE POWER OUTPUT DEPENDS ON A VARIABLE ENERGY SOURCE, BUT BETTER THAN WIND POWER	VERY POOR, SINCE THE TECHNOLOGY IS NOT EXPECTED TO HAVE WIDESPREAD USE IN 5-10 YEARS	7
4. DIESEL, GASOLINE	USUALLY VERY GOOD. LIMITED BY FUEL DELIVERY RELIABILITY AND MULTI-FUEL CAPABILITY	VERY VERSATILE, RANGING FROM <1 TO OVER 100 KW	EXCELLENT, CAN RESPOND TO LOAD CHANGES IN LESS THAN ONE SECOND. GOOD COLD START TIMES	EXCELLENT, POWER SYSTEMS COMMONLY AVAILABLE WORLDWIDE	1
5. CCVT	USUALLY VERY GOOD. IT HAS GOOD MULTI-FUEL CAPABILITY	LIMITED TO APPLICATIONS LESS THAN 5 KW REQUIRING VERY HIGH RELIABILITY	AVERAGE TO POOR. CAN RESPOND TO LOAD CHANGES IN MINUTES. COLD START TIMES ABOUT 15-20 MINUTES	GAINING ACCEPTABILITY FOR HIGH RELIABILITY USES SUCH AS TELECOMMUNICATIONS	4
6. FUEL CELLS	CAN ACCEPT A NUMBER OF FUEL TYPES INCLUDING BIOMASS BASED FUELS	40 KW STAND-ALONE FUEL CELLS BEING DEVELOPED FOR ARMY. COULD HAVE GOOD APPLICABILITY ELSEWHERE. 3-5 KW CELLS ALSO BEING TESTED	HAS MILLI/SECOND LOAD FOLLOWING ABILITY.	POOR, TECHNOLOGY IN TESTING AND EVALUATION PHASE, COMMERCIAL AVAILABILITY EXPECTED IN 1985-86	3
7. STIRLING	MULTI-FUEL CAPABILITY; LIQUIDS, SOLIDS, GASES, HEAT	20 KW SOLAR UNIT MAY BE AVAILABLE ABOUT 1985	ABOUT TWO MINUTES FOR COLD START, SLOWER RESPONSE THAN DIESELS	POOR. TECHNOLOGY IS TESTING AND EVALUATION PHASE	6

EXHIBIT 2-6
ACCEPTABILITY FACTORS

HYBRID CANDIDATE	SAFETY	ENVIRONMENTAL IMPACT	RANK
1. WIND	MAJOR CONCERNS ARE TOPPLING OF TOWER, FLYING BLADES AND ELECTRICAL SYSTEM MALFUNCTION.	POSSIBILITY OF LOW FREQUENCY NOISE AND TV INTERFERENCE, BIRD KILLS, AESTHETICS	6
2. HYDRO	NO SAFETY-RELATED PROBLEMS SHOULD OCCUR IN A WELL DESIGNED SYSTEM, DAM SAFETY COULD BE A PROBLEM	COULD CAUSE DISTURBANCES TO RIVER FLOW, RESERVOIR SYSTEMS WILL REQUIRE FLOODING OF LAND	4
3. WAVE POWER	NO SAFETY-RELATED PROBLEMS ENVISAGED, BUT INSTALLATION, MAINTENANCE, AND POWER TRANSMISSION COULD PROVE TO BE DANGEROUS	COULD VISUALLY IMPAIR COAST, COULD DAMAGE FISH SPAWNING GROUNDS. IT COULD BE BENEFICIAL IN PROVIDING COASTAL PROTECTION	7
4. DIESEL GASOLINE	FAMILIAR TECHNOLOGY WORLDWIDE, IF PROPERLY OPERATED NO SAFETY-RELATED PROBLEMS SHOULD OCCUR	AIR POLLUTION DUE TO EXHAUST, NOISE	5
5. CCVT	SAFE SYSTEM	AIR POLLUTION IS MINIMAL, NO NOISE PROBLEMS	1
6. FUEL CELLS	EXPECTED TO BE SAFER THAN THERMAL ENGINES	NO POLLUTION PROBLEMS ENVISAGED, QUIET OPERATION	2
7. STIRLING	UNSAFE OPERATING CONDITIONS HAVE NOT OCCURED IN PROTOTYPE MACHINES	NO NOISE OR UNDUE VIBRATION EXPECTED, MINIMAL AIR POLLUTION EXPECTED	3

EXHIBIT 2-7

OVERALL ORDINAL RANKING

HYBRID CANDIDATE	SELECTION CRITERIA RANK				OVERALL RANK
	AVAILABILITY	COST	APPLICABILITY	ACCEPTABILITY	
1. WIND	4	3	5	6	3
2. HYDRO	2	1	2	4	2
3. WAVE POWER	7	7	7	7	7
4. DIESEL GASOLINE	1	2	1	5	1
5. CCVT	3	6	4	1	4
6. FUEL CELLS	5	4	3	2	5
7. STIRLING	6	5	6	3	6

have lower cost, and high availability. PV/wave and PV/Stirling engine hybrid systems have low ranking because of unproven technology, low commercial availability and higher capital cost.

The following candidates were selected for more detailed analysis and evaluation:

- PV with 1-100 kW wind generators
- PV with 10-50 kW hydroelectric generators
- PV with 3 kW and larger internal combustion engine (IC) generators
- PV with 200W-5 kW CCVT generators
- PV with 40 kW or smaller fuel cells.

Both AC and DC power systems are considered. The DC system is primarily for low power ($\leq$ 5 kW) applications generating up to 10 kWh/day.

The PV/wind hybrid systems were selected because of the current availability of commercial wind turbines and the high economies of scale associated with wind machines. The system has no fuel cost, low O&M cost, moderate reliability (improvements expected in 5-10 year time-frame), few safety problems, and low environmental impact. The PV/hydro system was selected for similar reasons as the PV/wind. The hydro turbine component is an established and well proven technology with medium cost, low O&M cost, high reliability, long life, and zero fuel cost. The PV/IC generator system is the most accepted system because the IC component has been used for a long time and therefore is widely known. The PV/CCVT system was selected because of its high capacity factor, low O&M cost and very high reliability. The CCVT is currently commercially available. The last PV system selected was PV/fuel cell, because it is expected to have high capacity factors, low O&M costs, and high reliability.

2.4 System Operating Protocol

The five selected PV hybrid systems will use the generalized operating protocol shown in Exhibit 2-8. The systems can be grouped into two categories. The first is the environmentally dependent energy supply systems and the second is the liquid or gaseous fuel supply dependent systems. The main difference between these two is that in the first case power can be generated only when the resource is available (wind, water, sun). In the second case, power can be supplied on demand. This makes environmentally dependent systems less reliable (unless there is energy storage) than fuel dependent systems, but they have lower O&M costs and no fuel costs.

EXHIBIT 2-8

GENERALIZED OPERATING PROTOCOL

1. <u>Environmentally Dependent Energy For Alternative Power Source</u>

   Since the "Fuel" supply is usually not controllable, electricity is generated by the PV Array and the alternative power source whenever possible. The generated power is distributed according to the following priority:

   1. Load
   2. Batteries
   3. Dissipated

   If generated power is inadequate, power to the load is supplied by the batteries.

2. <u>Liquid or Gaseous Fuel Supply</u>

   Three protocols are feasible:

   1. PV and alternative power source operates in parallel. The battery provides "peaking" power.

   2. PV provides power during the daylight hours and the alternative power source is used during the night.

   3. PV provides all the power requirements and the alternative is used as a standby power source.

2.5 Preliminary System Configurations

This section discusses the design/control philosophy and equipment requirements for the five selected PV hybrid systems. The purpose of this investigation is to ensure that feasible operating procedures and realistic costs are used in the detailed performance and cost analyses to be conducted later.

Two system sizes are considered: large (all AC), and small (all DC). The power level that divides systems into large and small categories will depend on the available resources, the economics, and the performances. Simulations will be needed for both types of systems to determine their energy delivery and costs for various equipment sizes. The power level at which AC systems become more cost effective will then be determined by these simulations and the corresponding economic analysis.

The division between small and large systems is important because the economies of scale enter in large systems but not in small. The equipment used in small systems is kept simple. For example, PV peak-power trackers are not used for small systems and the loads are supplied DC. In large systems, a sophisticated, high-efficiency inverter can be justified, along with the approximately $2000 expense of a peak power tracker. Multiple voltages are also more likely in the large systems, because it is important that it supply AC for ease of transformation.

2.5.1 PV/Wind Hybrid Systems

Two systems (large and small) will be considered for this hybrid configuration. These PV/wind systems require batteries to maintain the required system availability.

The following is a discussion of the design/control philosophy. Exhibit 2-9 and 2-10 show the system configurations. The suggested design for the small PV/wind system (Exhibit 2-9) uses battery storage for energy generated by the wind and PV subsystems. The PV system would be controlled by a partial-shunt regulator. When the battery is fully charged, and there is insufficient demand from the load, this regulator short-circuits some of the modules and reduces the output voltage to prevent overcharging of the battery. Because this system operates at specific voltages, it is customary to allow the regulator to periodically apply the full PV-system voltage to the battery. Thus, the battery can be maintained at full charge without having a low constant charge rate. Because the regulator is non-dissipative, it has high reliability.

The wind system should have a brushless permanent-magnet alternator with permanently lubricated bearings, to minimize maintenance requirements. The AC power generated by the wind generator is rectified to DC and supplied to the load. Many loads can accept DC (brushless DC motors, incandescent lights, communications equipment,

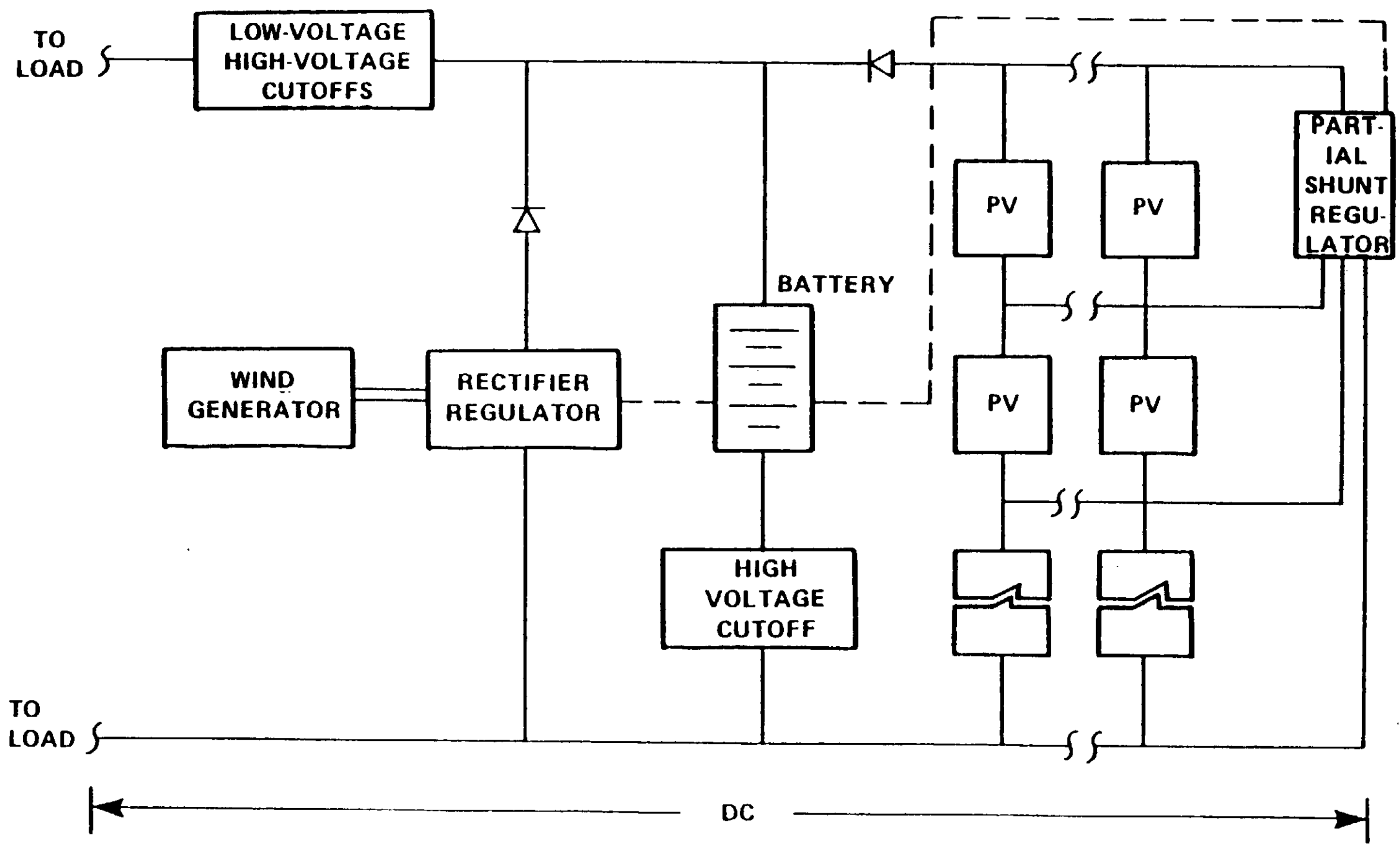


EXHIBIT 2-9: SMALL PV/WIND HYBRID SYSTEM SCHEMATIC

etc.). However, if AC is needed because DC equipment is unavailable, dedicated inverters can be used. These inverters would not operate unless the device was turned on; therefore, they would always operate at peak load and peak efficiency.

In addition to the major controls, circuit breakers and current limits would be needed. High and low-voltage cutoffs would be required to protect the battery. Ground-fault detectors and lightning protection would also be required.

Like the small PV/wind system, the large PV/wind system requires batteries to maintain a continuous supply of power (Exhibit 2-10), although the load would be supplied AC. This system is large enough that a sophisticated, high efficiency, central inverter can be used, complete with peak-power tracking. (A pilot-cell system might be required for the peak-power tracker to differentiate between array power and battery power.) To simplify controls, the wind system AC power is rectified, fed to the DC bus and then inverted.

To provide the desired priorities, the control system may require that the wind output, PV output, load and battery state-of-charge be known. A microprocessor controller could then perform the controlling function. However, a simpler system may be possible: the battery voltage monitoring system can be designed so that no energy is passed from the DC side of the system to the AC side unless the AC voltage has dropped below, for example, 220 volts. The wind system would be designed to supply 230 volts, and would charge the battery only if the differential exceeded 10 volts. Safety and disconnect techniques required for the small PV/wind system would also be required for the large system.

This system might be more cost effective if it were a three-way hybrid, being combined with multiple engines. However, such systems are beyond the scope of work of this study.

2.5.2 PV/Hydroelectric Generator Systems

Two system sizes are considered. The smaller systems use batteries to maintain the required system availability. The large systems might use the energy stored in the water or the energy stored in batteries, depending on the rainfall pattern and water storage capability, to maintain high availability. The suggested design for the small PV/hydro system (Exhibit 2-11) uses battery storage for the PV subsystem and a reservoir for the hydro system. The PV system would be controlled by a partial-shunt regulator. The hydro turbine would probably have a permanent-magnet alternator with rotating rectifiers, no brushes and permanently lubricated bearings, to minimize maintenance requirements. Speed control would be maintained by an inlet valve or an electronic dissipative controller. In addition to the major controls, circuit breakers and current limits would be used. High and low-voltage and over-current cutoffs would be required to protect the battery. Ground-fault detectors and lightning protection would also be required.

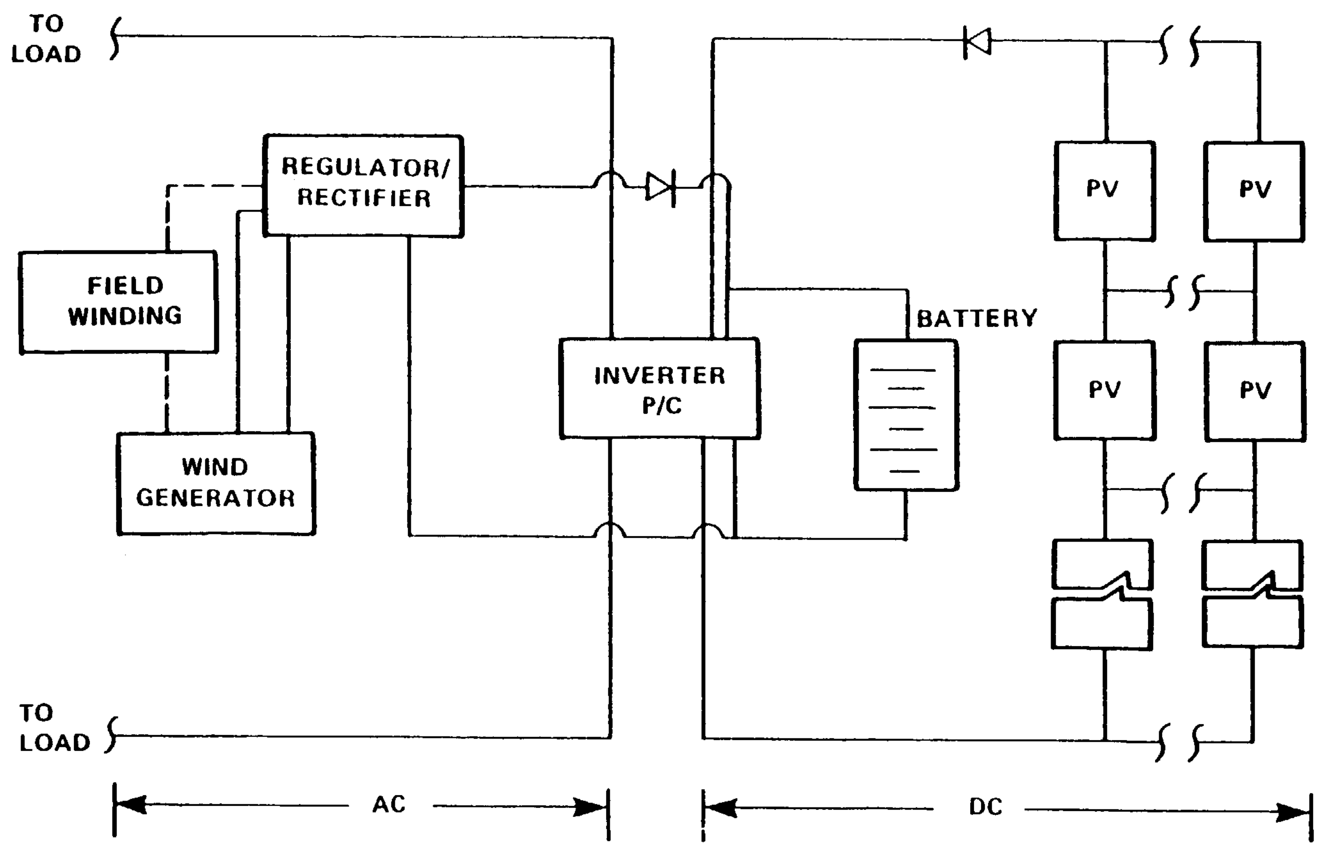


EXHIBIT 2-10: LARGE PV/WIND HYBRID SYSTEM SCHEMATIC

Like the smaller PV/hydro system, the larger PV/hydro system (1000 kWh/day) requires batteries or hydro storage to maintain a continuous supply of power (Exhibit 2-12). The load would be supplied AC. This system is large enough that a sophisticated, high-efficiency, central inverter can be used, complete with peak-power tracker. The hydro system would be several tens of kilowatts. To simplify controls the hydro system output would be rectified and fed to the DC bus. The load would be supplied AC through the inverter. To provide the desired priorities, the control system may require that the hydro output, PV output, load and battery state-of-charge be known. A microprocessor controller could then perform all the controlling functions. Safety and disconnect techniques required for the small PV/hydro system would also be required for the large system.

The tradeoff between water and battery storage will depend strongly on the rainfall pattern for both large and small systems. The details of the load profile will also be important. The high efficiency of batteries favors battery storage; the low lifecycle cost of reservoirs favors hydro storage. If the storage requirements are dictated by a brief rainy season, the excess rainfall might provide sufficient storage. If the load has many short spikes, such as might occur in the small system where load factor diversity is poor, at least some battery storage will be desired. Therefore, any system simulated should provide for both battery and hydro storage and the economic optimization should dictate the proportion of each.

In all cases, to make a PV/hydro system economically viable, it may be necessary to assume that the dam can be justified for nonpower purposes (e.g., for irrigation or flood control).

2.5.3 PV/Internal Combustion Engine Generator Systems

The small PV/engine system (Exhibit 2-13) would be the same as the small PV/wind system, except that the wind generator would be replaced by the engine. Since small engines, and large engines run at part-load are inefficient, and since lightly loaded engines require more maintenance than heavily loaded engines, the engine controls for the small system should be designed to cycle the engine rather than modulate its output, (i.e. the engine would be used to charge the batteries). As in the small PV/wind system, the load would be supplied DC; dedicated inverters would be used on the equipment requiring AC.

The reliability of this system will depend strongly on the reliability of starting the engine. Therefore, an operator would be required in case the automatic startup did not occur. A low-voltage signal would alert the operator.

Two options are possible for the large PV/engine system (Exhibit 2-14). One would be similar to the large PV/wind system. The other

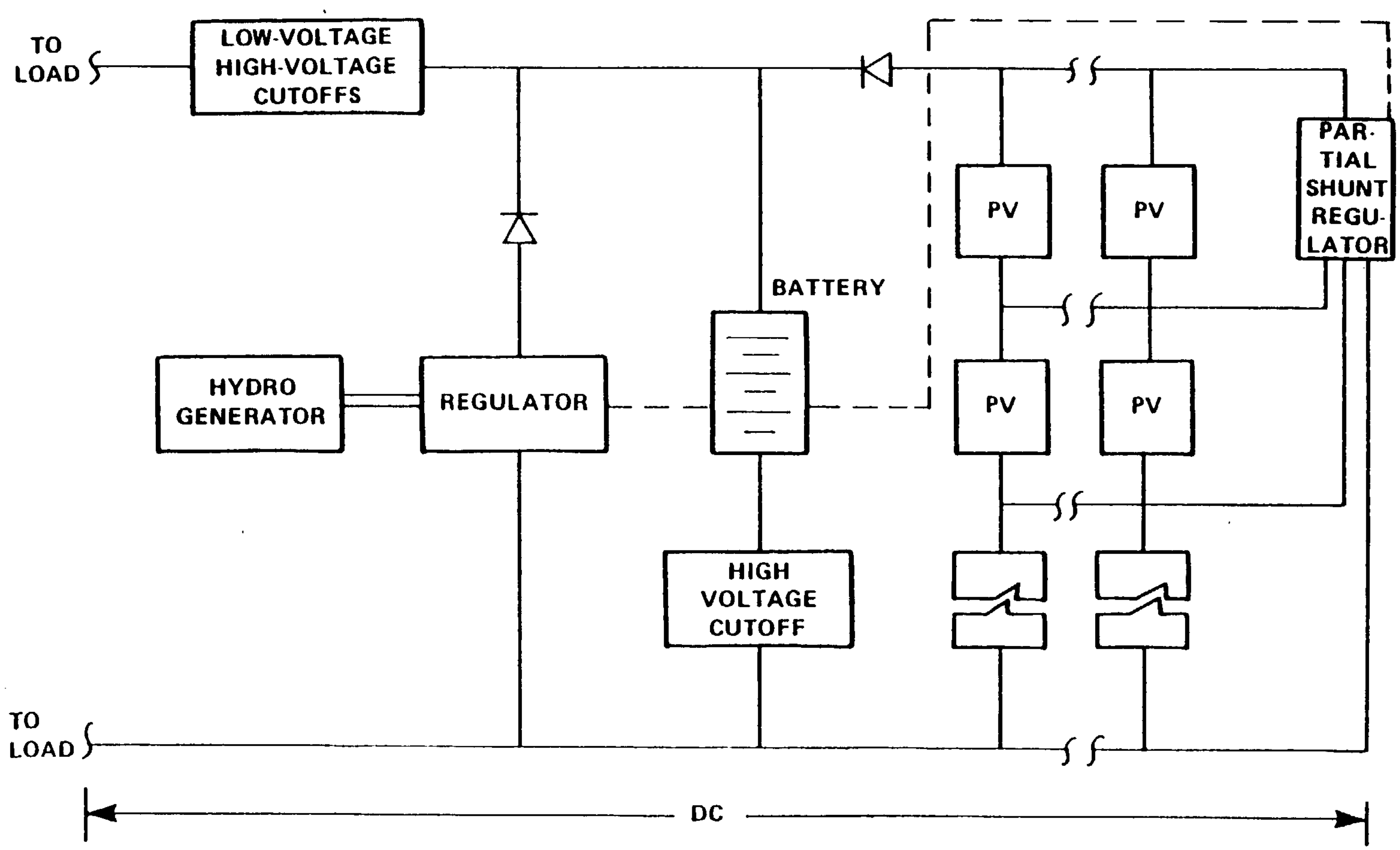


EXHIBIT 2-11: SMALL PV/HYDRO HYBRID SYSTEM SCHEMATIC

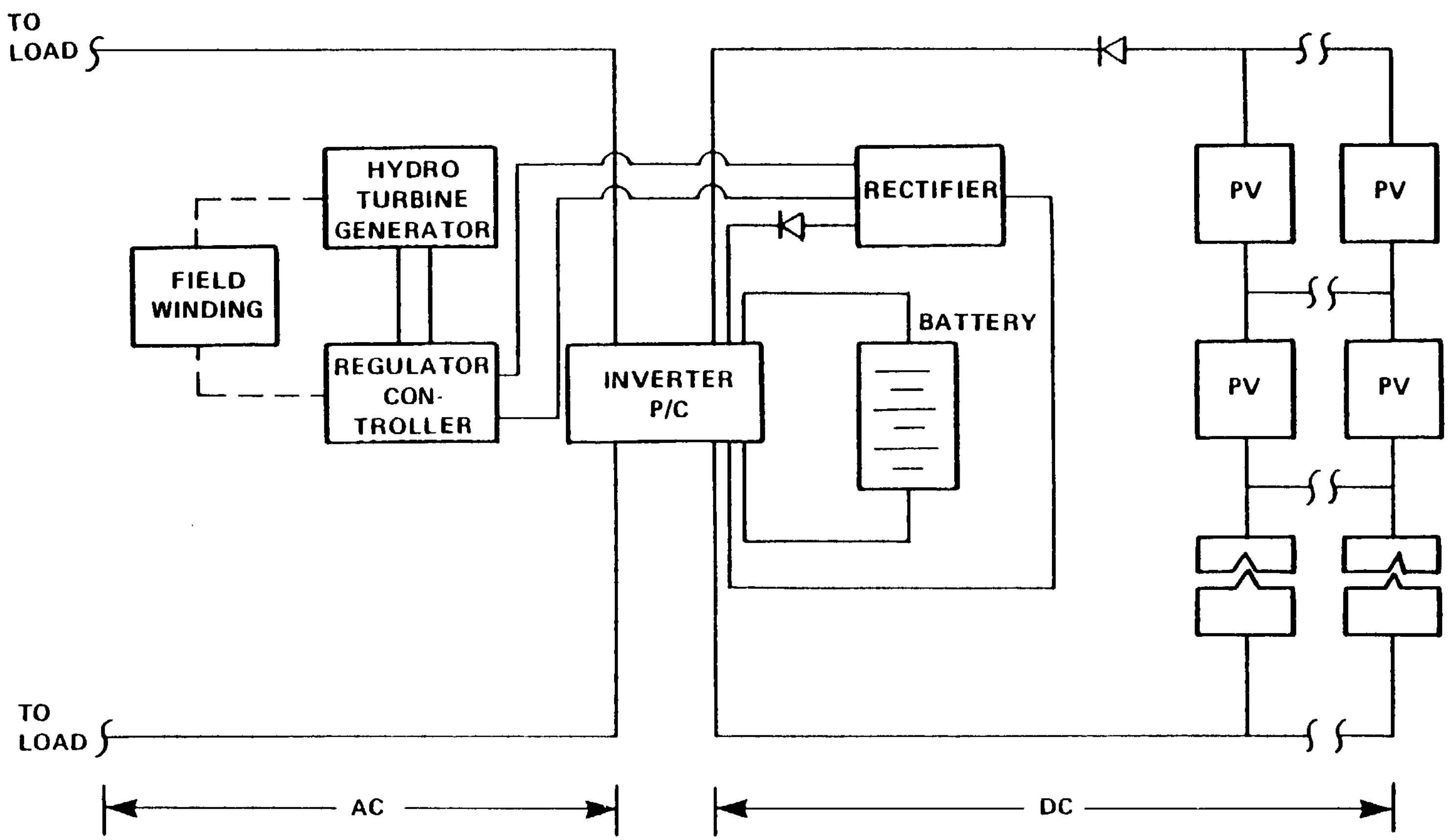


EXHIBIT 2-12: LARGE PV/HYDRO HYBRID SYSTEM SCHEMATIC

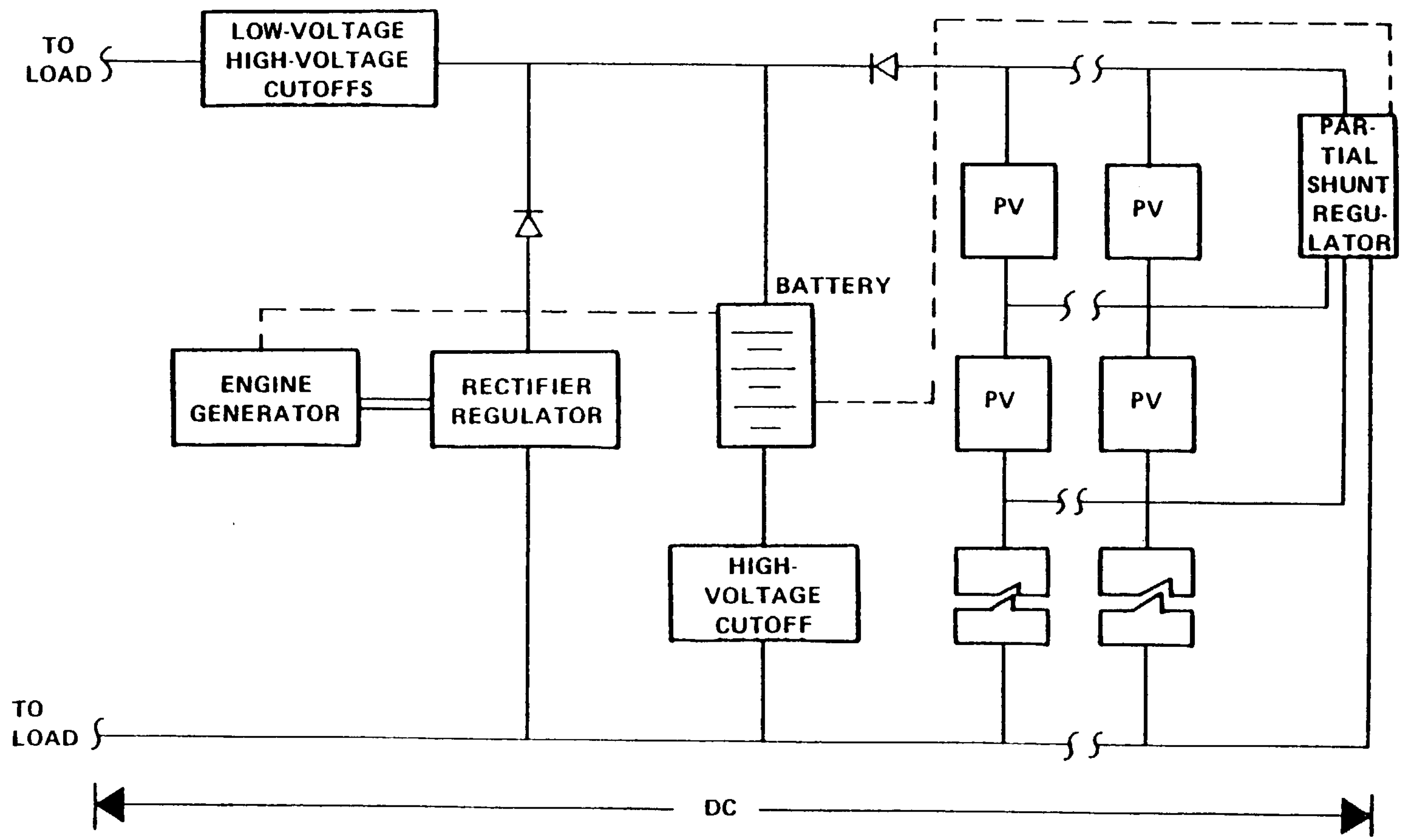


EXHIBIT 2-13: SMALL PV/IC ENGINE HYBRID SYSTEM SCHEMATIC

would omit the battery, relying instead on the chemical storage of the engine fuel; in this case, the PV system would be merely a fuel saver. This system would find favor in locations with high fuel costs.

Multiple engines may be needed to permit the operating engines to be run near peak capacity, thereby avoiding the low efficiency/-high maintenance aspects of part-load operation. The engines would be cycled to keep the wear uniform and to keep them all in satisfactory operating condition.

2.5.4 PV/CCVT System

Due to the high capital cost of the CCVT and its low fuel efficiency, it is an appropriate power source for very high reliability, remote, low power applications. The suggested design for the small PV/CCVT system (Exhibit 2-15) uses PV and batteries as the primary power source. The backup CCVT is used only for unusual strings of bad weather and for months when the insolation is low.

In addition to the major controls, circuit breakers and current limiters will be used. High- and low-voltage cutoffs would be required to protect the battery. Ground-fault detectors and lightning protection would also be required.

2.5.5 PV/Fuel Cell System

The suggested design for the small PV/fuel cell system (Exhibit 2-16) uses PV and batteries as the primary power source. The backup fuel cell is used for extended periods of bad weather and for months when insolation is low. Fuel cell costs $2500/kW are required for this system to be cost effective relative to small PV/diesel or gasoline generators. The PV system output could be controlled by a partial-shunt regulator. Since fuel cells produce DC, a DC distribution system is clearly favored for these systems. The system would require controls, circuit breakers, current limiters, high- and low-voltage cutoffs to protect the battery, ground-fault detectors and lightning protection.

The large PV/fuel cell system (Exhibit 2-17) is large enough that a sophisticated, high-efficiency, central inverter can be used, complete with peak-power tracking. In all other respects, the large-system concept is the same as for the small system.

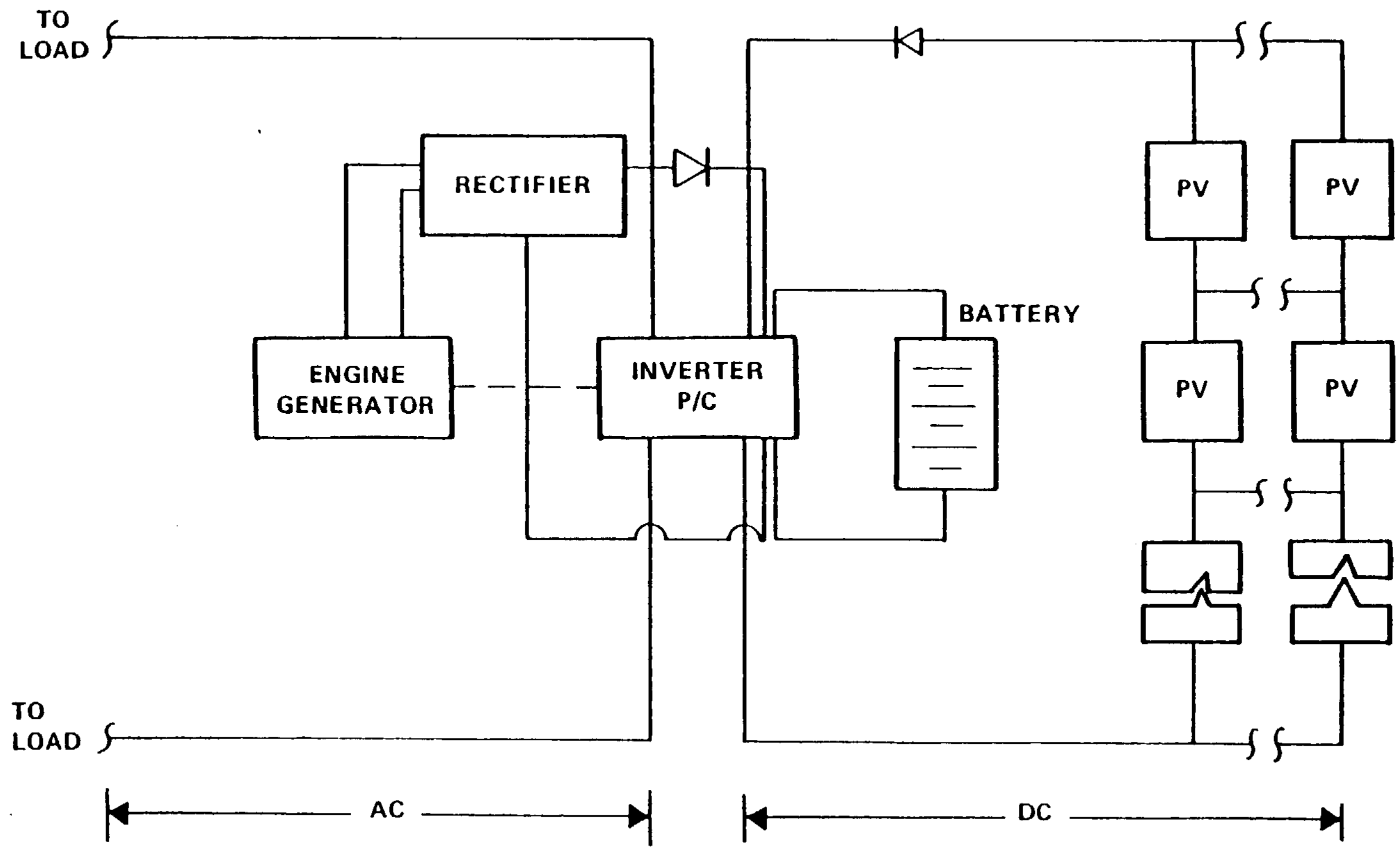


EXHIBIT 2-14: LARGE PV/IC ENGINE SCHEMATIC

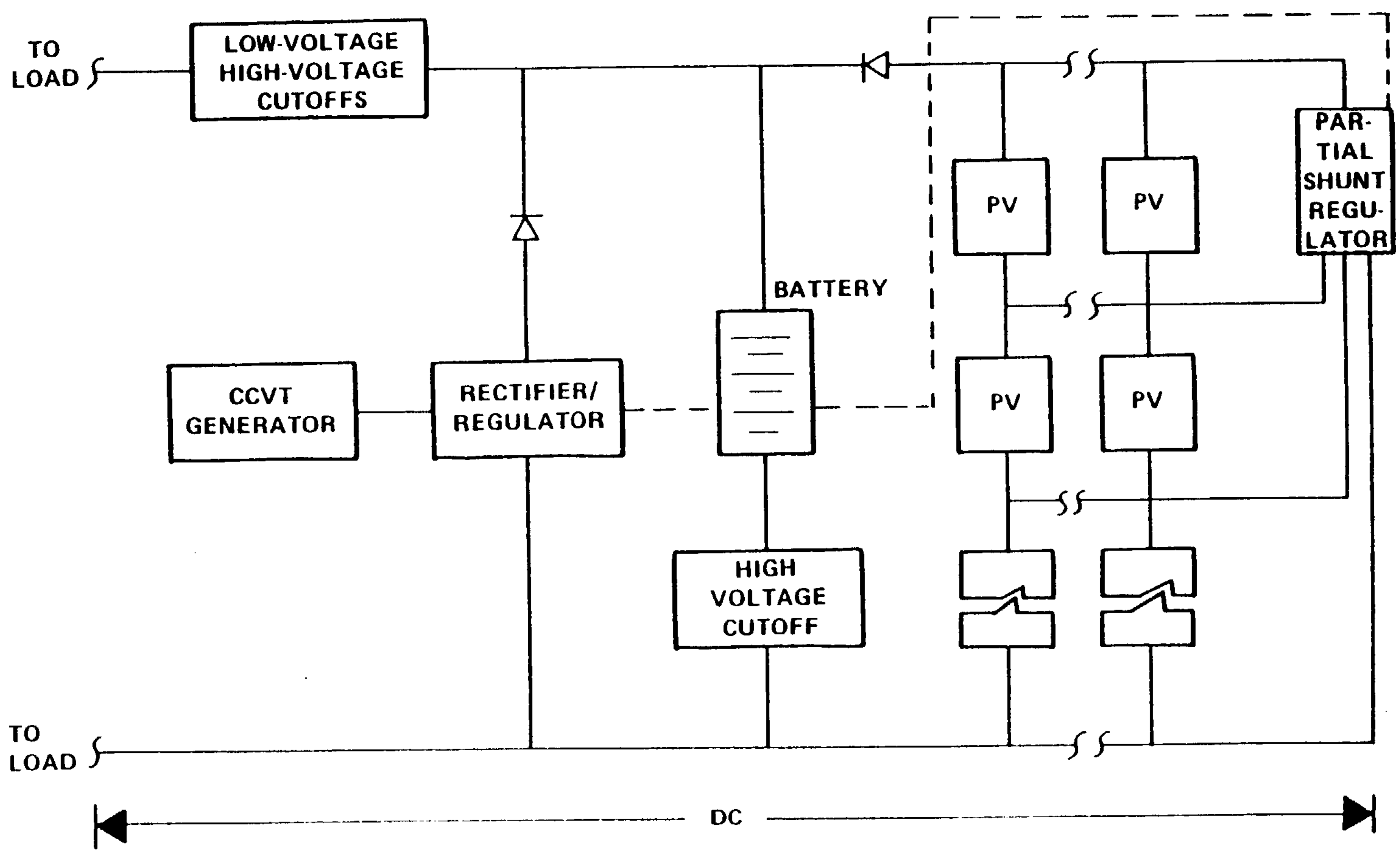


EXHIBIT 2-15: PV/CCVT HYBRID SYSTEM SCHEMATIC

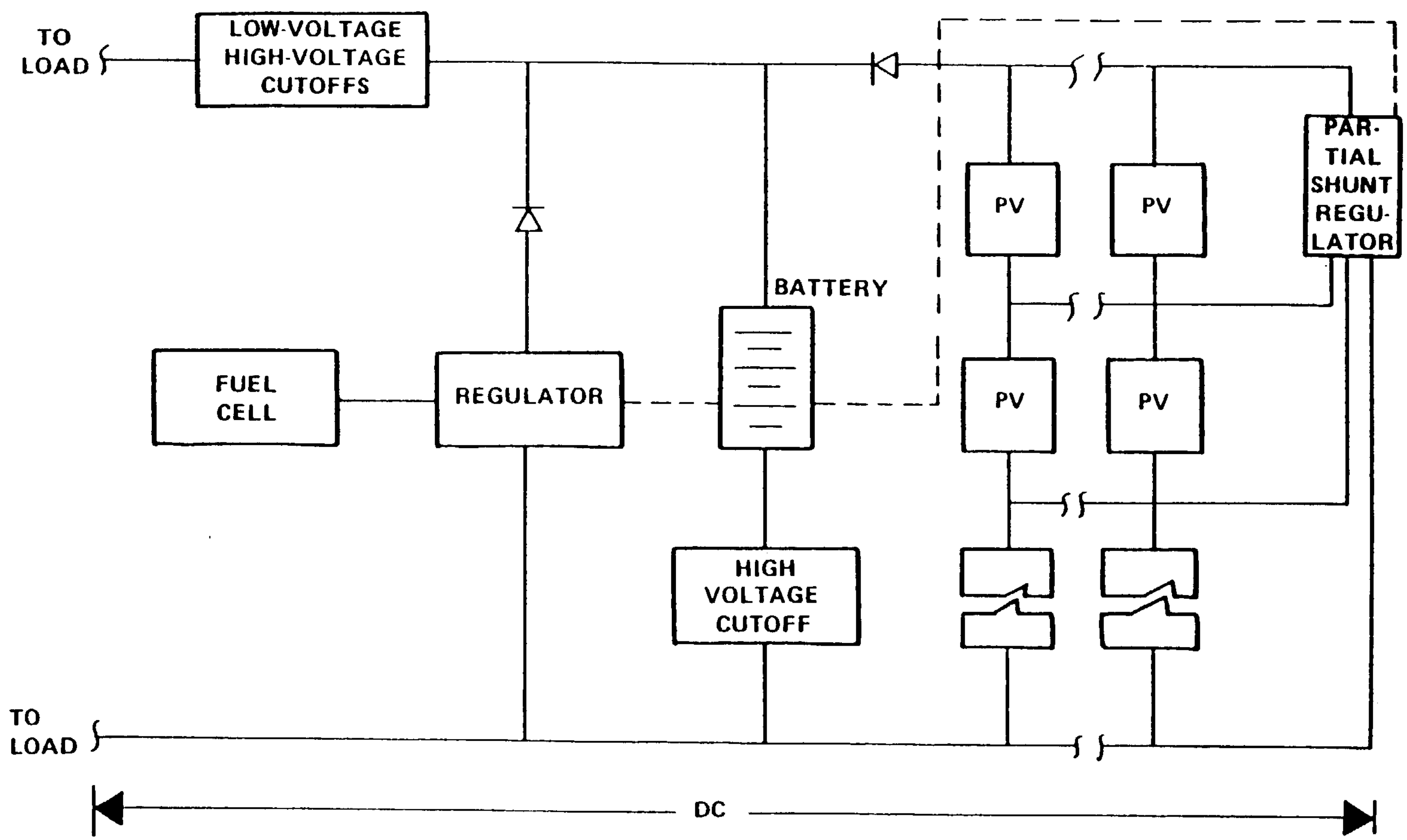


EXHIBIT 2-16: SMALL PV/FUEL CELL HYBRID SYSTEM SCHEMATIC

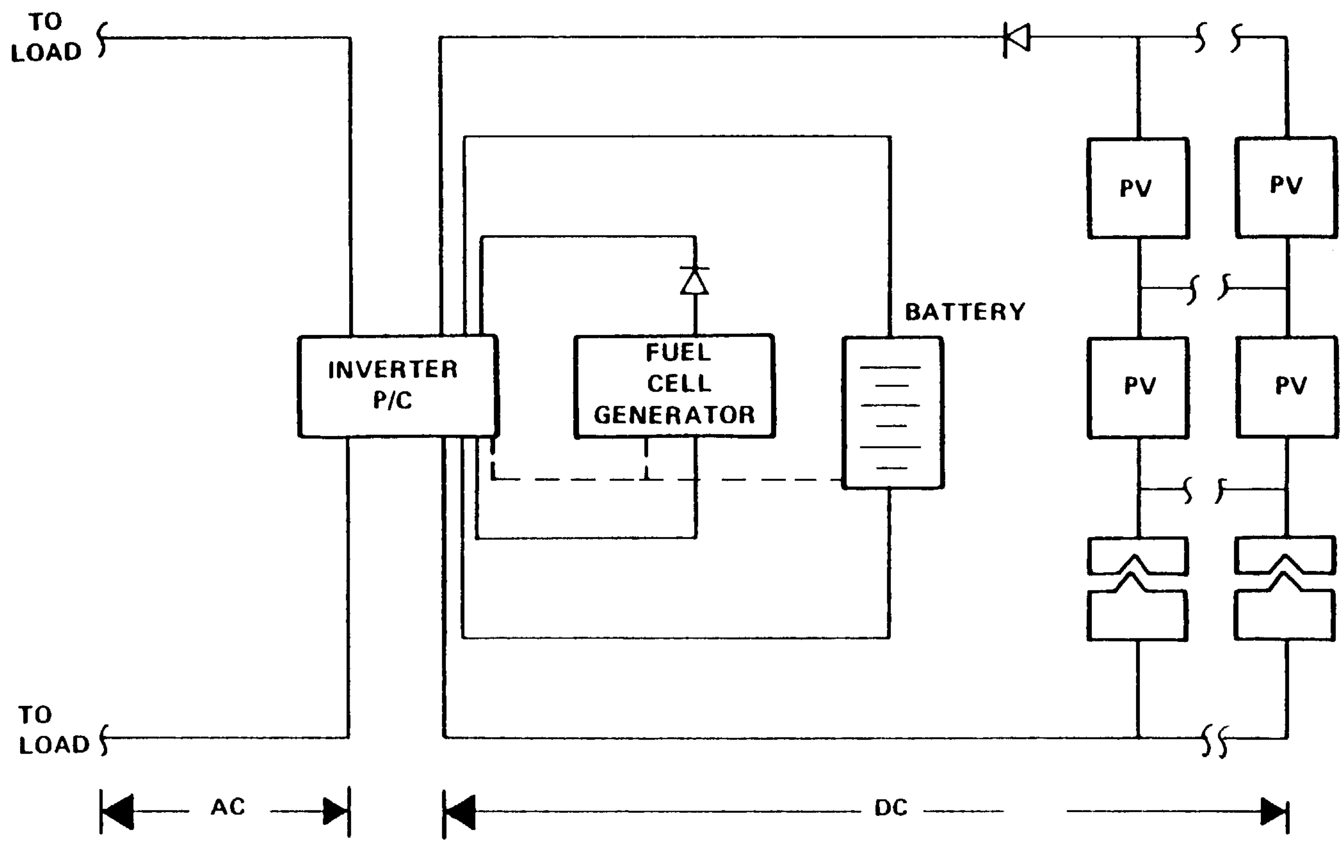


EXHIBIT 2-17: LARGE PV/FUEL CELL HYBRID SYSTEM SCHEMATIC

3.0 OVERVIEW OF THE SIMULATION MODELS

There are two generic simulation models. The first is the model which sizes, costs and simulates the performance of a hybrid system consisting of PV and a generator whose input energy is environment dependent. The PV/wind and PV/hydro hybrids, fall into this category. The second is the model which sizes, costs, and simulates the performance of a hybrid system consisting of PV and an engine generator that requires liquid or gaseous fuel. The PV/diesel, PV/CCVT and PV/fuel cell hybrids fall into this category.

Source code listings of the computer models are shown in Appendix A.

3.1 PV/Wind or Hydro Hybrid Model

Exhibit 3-1 shows the major components of the PV/wind or hydro model. The two models consist of the following major components:

- Stochastic hourly insolation generator
- Stochastic hourly windspeed generator
- Hourly stream flow generator
- PV and battery sizing model for a specific wind energy conversion system (WECS) or a hydroturbine
- System levelized electricity cost calculation model
- System performance simulation model.

The model using hourly resource and demand profiles, calculates the PV array and battery size for a given WECS or hydroturbine. Next it simulates the performance of the hybrid system over a year and calculates its resource availability (percent of time demand was satisfied given 100 percent equipment availability), percent of demand satisfied, levelized energy costs, and initial capital cost. The following sections describe the major model components.

3.1.1 Stochastic Hourly Insolation Generator

The program to generate hourly solar insolation data first calculates daily average insolation using the procedure in Macomber.[1] The

1 Macomber, H.L., et al., "Photovoltaic Stand-Alone System: Preliminary Engineering Design Handbook," DOE/NASA/0195-1, NASA CR-165352, August 1981. Exhibit 11.3-1 page 11-16.

average insolation values are randomized using the generalized clearness index (KH) distribution data in Macomber. For computation purposes, a Beta distribution was used to fit the data. For each day of the year, a random KH is calculated using the Beta distribution parameters corresponding to average insolation for that day.

Once the random average daily insolation values are calculated, hourly insolation values are computed using the method developed by Munroe.[1] The calculated values are stored in a data file (365 days * 24 hourly values) for use in the system sizing and simulation routines.

A sample run showing the input data requirements is shown in Exhibit 3-2. A plot of the daily total insolation based on data generated by the model is shown in Exhibit 3-3.

3.1.2 Stochastic Hourly Wind Speed Generator

The procedure requires as input data, an average annual diurnal wind profile, monthly average wind speed and an index indicating the variability of the wind[2]. The average annual hourly wind profile and the monthly average wind speed are interpolated to calculate the average hourly wind speed for every hour in a year. Next, since the actual wind speed in any hour could vary substantially about the mean, the Weibull distribution is used to estimate a random hourly wind speed. The randomization procedure used is given in Mikhail.[3]

A sample run showing input data requirements is shown in Exhibit 3-4. Note that the diurnal profile specification requires at least two data points and at most 24 data points. Exhibit 3-5 shows a plot of wind speed as a function of day for a sample data set.

3.1.3 Hourly Stream Flow Generator

The procedure uses monthly average streamflow data and by interpolation creates a 365x24 file of hourly streamflow data. Since streamflow on an hourly basis is very much less variable than insolation or wind speed, a stochastic flow generator is not used.

---

1 Munroe, M.M., 1979, "Estimation of Totals of Irradience on a Horizontal Surface from U.K. Average Meteorological Data," Solar Energy, Volume 24, pages 235-238.

2 This is a measure of the degree of variance of wind speed from the mean. It is used to calculate the k and c parameters in a Weibull probability density function.

3 Mikhail, A., "Wind Power for Developing Nations," Solar Energy Research Institute, No. DE 81-0-25-792, July 1981.

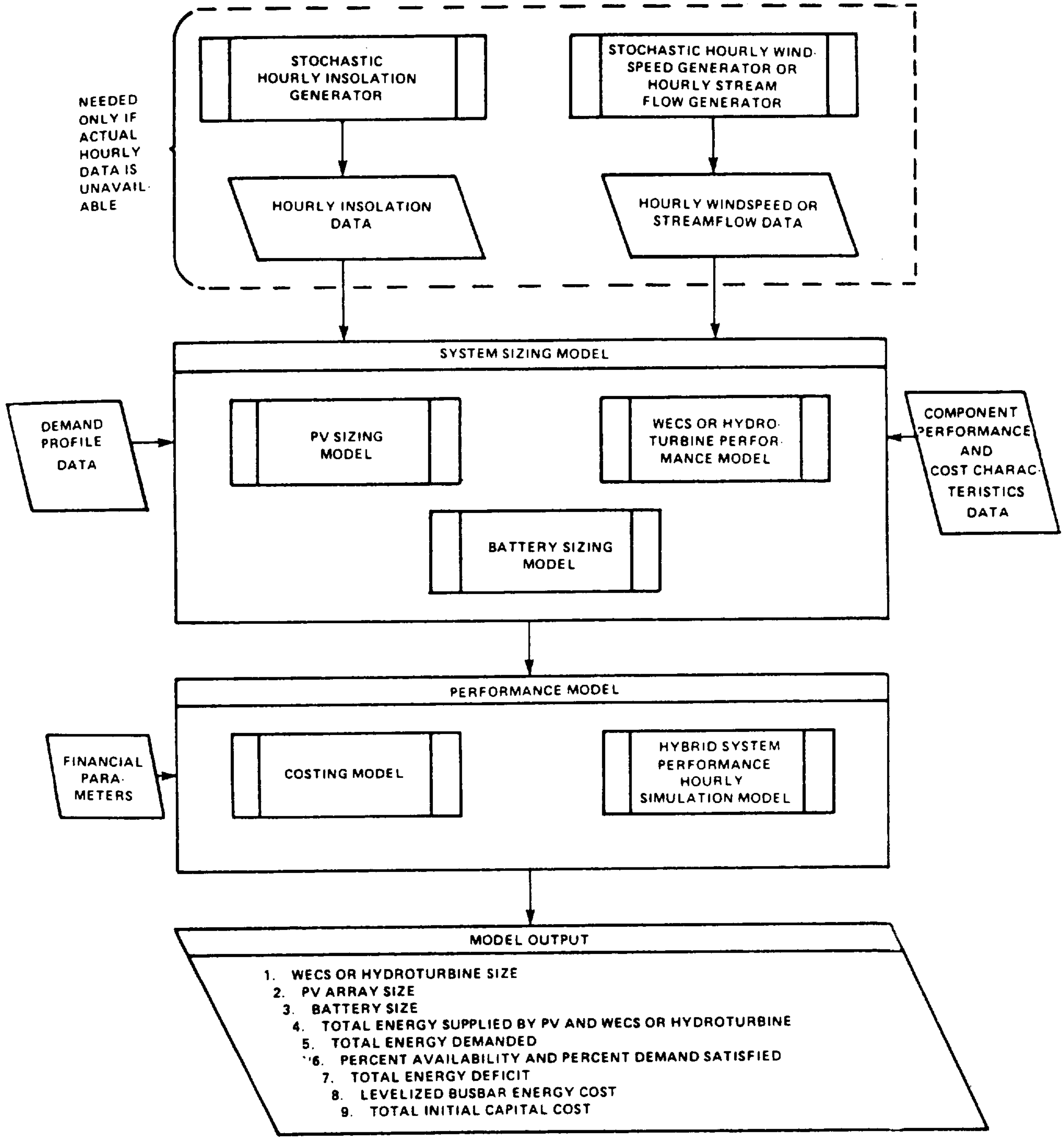


EXHIBIT 3-1: MAJOR COMPONENTS OF PV/WIND OR HYDRO MODEL

EXHIBIT 3-2

SAMPLE RUN OF STOCHASTIC HOURLY INSOLATION GENERATOR

```
@XQT SOLAR.
DO YOU WANT TO CHANGE THE RANDOM SEED? (1=YES,0=NO)
0
ENTER 12 CLEARNESS INDEXES
.345 .45 .49 .52 .609 .58 .63 .68 .64 .47 .4 .30
LATITUDE (DEGREES) ?
38.25
GROUND REFLECTANCE RHO ?
.1
ARRAY TILT ANGLE ?
35.
                      BETA PRMTRS
       JUL  CLRN.    -----------
MONTH  DAY   IND       P      Q
-----  ---  -----    -----  -----
  1      1   .345     1.30   2.42
  2     32   .450     1.99   2.29
  3     60   .490     2.39   2.38
  4     91   .520     2.63   2.33
  5    121   .609     4.18   2.39
  6    152   .580     3.04   2.11
  7    182   .630     6.52   3.20
  8    213   .680    12.09   5.13
  9    244   .640     7.64   3.59
 10    274   .470     2.19   2.34
 11    305   .400     1.50   2.18
 12    335   .300     1.13   2.63

 HISTOG-------------------------------------------------------------
 10  *IIIIIIIIIIIIII                                               *
  9  *IIIIIIIIIIIIIIIII                                            *
  8  *IIIIIIIIIIIIIIIIIIIIIIIIIIIIII                               *
  7  *IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII                  *
  6  *IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII               *
  5  *IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII        *
  4  *IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII   *
  3  *IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII              *
  2  *IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII             *
  1  *IIIIIIIII                                                    *
--------------------------------------------------------------------
FREQUENCY   5    10    15    20    25    30    35    40    45    50    55
            ONE FREQUENCY UNIT IS EQUAL TO     1  'COUNT' UNIT(S)
```

EXHIBIT 3-3

INSOLATION DATA GENERATED BY STOCHASTIC
HOURLY INSOLATION GENERATOR

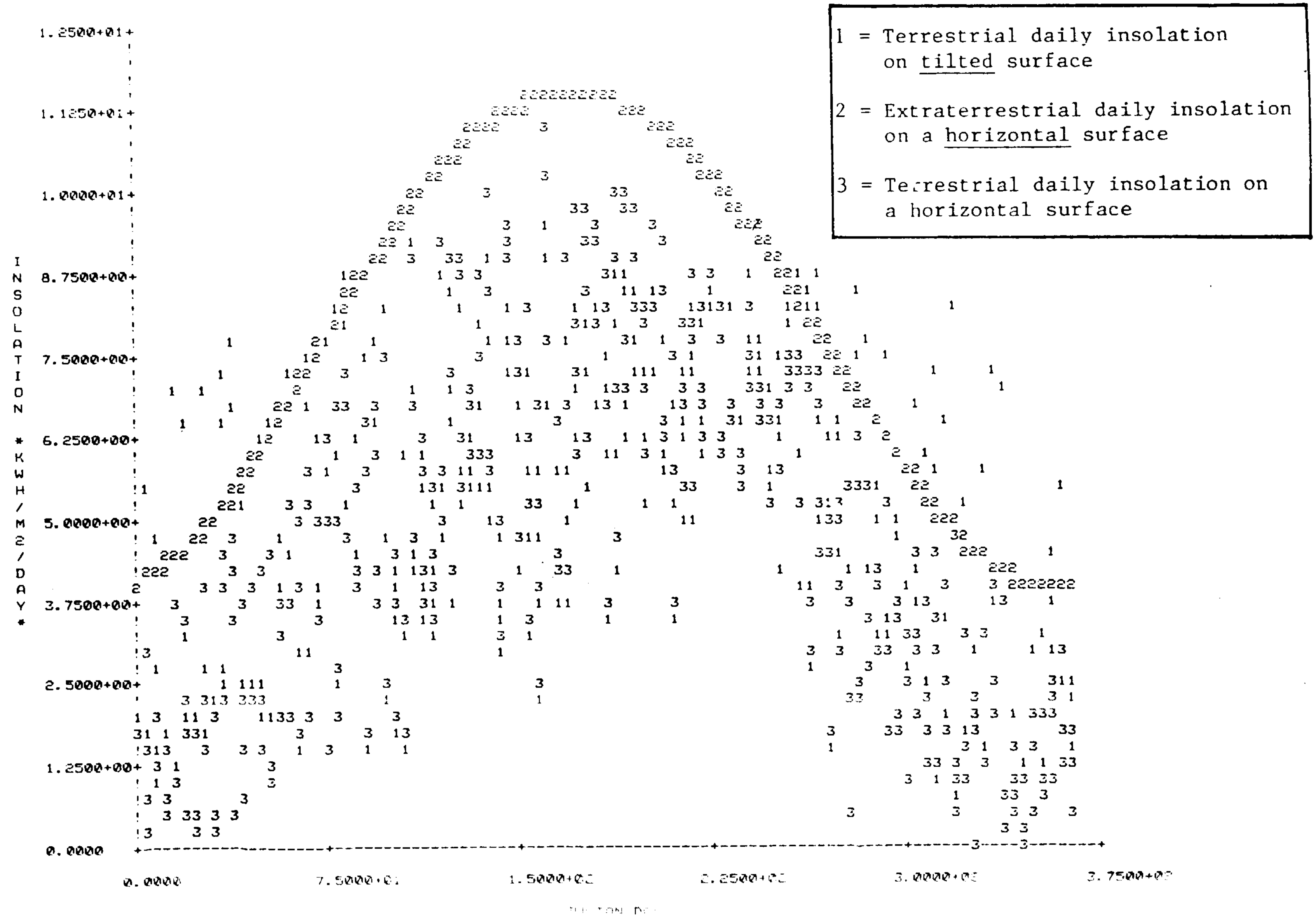


EXHIBIT 3-4

SAMPLE RUN OF STOCHASTIC HOURLY
WIND SPEED GENERATOR

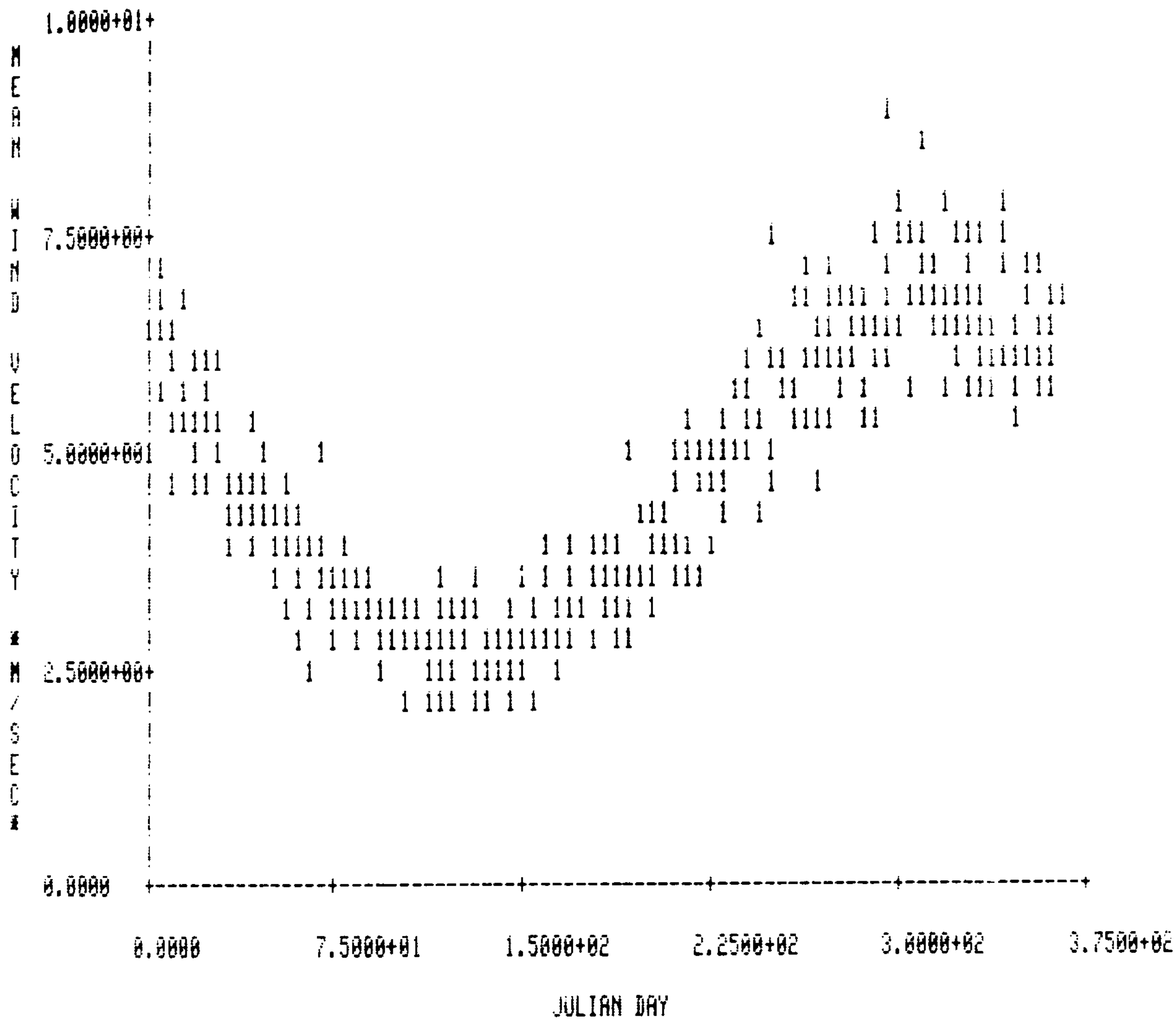
```
@..OT WIND.
DO YOU WANT TO CHANGE THE RANDOM SEED? (1=YES,0=NO)
0
# OF AVAILABLE HOURLY MEAN VALUES ?
3
ENTER TIME AND CORRESPONDING MEAN WIND SPD (M/SEC)
1,10.
12,5.
23,9.
10.00    9.55    9.09    8.64    8.18    7.73    7.27    6.82    6.36    5.91    5.45    5.
00
 5.36    5.73    6.09    6.45    6.82    7.18    7.55    7.91    8.27    8.64    9.00    9.
50
ENTER 12 MONTHLY MEAN WIND SPEEDS
10. 9. 8. 7. 6. 5. 4. 5. 6. 7. 8. 9.
ENTER VARIABILITY (1,2 OR 3)
3
MIN=   .035
MAX= 25.524
  1112.   2161.   2077.   1624.   926.   521.   236.   76.   24.   3.

   ---------------------------------------------------------------------
 HISTOG---------------------------------IIIIIIIIIIIIIIIIIIIIIIIIIIIIII                                  ◆
 10  ◆IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII ◆
  9  ◆IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII   ◆
  8  ◆IIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIIII                ◆
  7  ◆IIIIIIIIIIIIIIIIIIIIIIIIII                                   ◆
  6  ◆IIIIIIIIIIIIII                                               ◆
  5  ◆IIIIII                                                       .
  4  ◆II                                                           .
  3  ◆                                                             .
  2  ◆                                                             ◆
  1  ◆
---------------------------------------------------------------------
FREQUENCY  5   10   15   20   25   30   35   40   45   50   55   60
           ONE FREQUENCY UNIT IS EQUAL TO   36  'COUNT' UNIT(S)


STOP    NORMAL EXIT
```

EXHIBIT 3-5

GRAPH OF SAMPLE OUTPUT FROM STOCHASTIC
HOURLY WIND SPEED GENERATOR



3.1.4 PV and Battery Sizing Model

The sizing model selects a specific WECS or hydroturbine and calculates the corresponding size of the PV array and battery needed to satisfy the demand. PV array is sized so that the total energy supplied is equal to the energy demanded by the load minus the energy supplied by the WECS or hydroturbine in any given period of n days. The length of the period, "n", can be varied from one day to 365 days. As "n" increases the required array size decreases, since random fluctuations in resource availability tend to get dampened. The battery is sized to enable it to supply the net energy demanded (energy demand - PV output - wind or hydro output) in any given day.

The PV array performance at any given hour is modeled as follows:

Array output (kW) = Insolation (kW/m2) *Array Size (m2)* (Given Efficiency)

The WECS hourly output is simulated using the equations developed by Chou and Corotis.[1] The performance model requires as input: hourly wind speed, rated power output (kW), machine characteristics (cut-in speed, cut-out speed, rated speed in m/s and hub height).

The hydroturbine performance is calculated using the following equations:

Hydroturbine output (kW) = 9.81 * efficiency * head(m) * flow rate (m3/sec)

where efficiency is a given function of flow rate. Turbine operating range is also given.

The battery is modeled as a constant voltage energy storage device, with user specified maximum charge and discharge rates, efficiency and an allowable minimum state of charge. The battery is sized to allow it to provide the maximum cumulative daily energy needed from the battery. Once the maximum daily storage (MDS) requirements are determined, battery size is calculated by multiplying MDS by a user specified number of days of storage. This allows energy availability to be increased to allow for days with unexpectedly low insolation and/or wind or hydro power.

The sizing procedure is repeated for all the WECS or hydroturbines specified by the user.

---

1 Chou, K.C. and R.B. Corotis, "Simulation of Hourly Wind Speed and Array Wind Power," Solar Energy, Volume 26, 1981, pages 199-212.

3.1.5 Levelized Cost Estimation

Levelized busbar cost is used to measure the cost of energy from the hybrid systems under investigation. The procedure used is the utility revenue requirements methodology developed by the Electric Power Research Institute and reported in their Technical Assessment Guide.[1]

The methodology takes into account the following cost components:

- Plant capital cost for each of the following:
  - PV array ($\$/kW_p$)
  - Balance of systems related to PV array ($\$/kW_p$)
  - Alternate generator ($)
  - Balance of systems related to alternate generator ($/Rated alternate generator capacity)
  - Battery ($/kWh of storage)
  - Balance of system for combined system ($)
- Fuel usage, if any, associated with each of the above hybrid system components (units/year)
- Operation and maintenance costs associated with each of the above hybrid system components. (Specified as percent of capital costs for PV, WECS, and hydropower generators and as $/hour of operation for diesel and gasoline generators, fuel cells and CCVT).

It also requires the following financial parameters:

- Debt, preferred stock and common stock rates of returns
- Debt and equity ratios
- Depreciation
- Type of accounting procedure (flow through or normalization accounting)
- Investment tax credits
- Income tax rates
- Federal, state, local and property tax rates

---

1 Electric Power Research Institute, "Technical Assessment Guide," EPRI PS-1201-SR, July 1979, and EPRI P-2410-SR, May 1982.

- Insurance rates
- Fuel costs
- Escalation rates for capital equipment, O&M costs and fuel, and inflation rate
- Tax and book life of equipment and plant.

The costing procedure calculates the levelized busbar cost of electricity supplied to the load by the PV hybrid system.

3.1.6 System Performance Simulation Model

The PV hybrid system is simulated on an hourly basis for a year, using the stochastic resource profiles and the component performance models described previously. The model dispatches energy generated first to the load, next to the batteries and finally, if there is excess energy, it is dumped. If the generated energy is inadequate, then the battery is discharged.

The output from the PV/wind or hydro hybrid models are the following:

- PV array size
- Alternate generator size
- Battery size
- Total energy supplied by the PV array
- Total energy supplied by the alternate generator
- Total demand
- Percent of the time that demand is satisfied, assuming 100 percent equipment availability
- Percent of the energy demand satisfied
- Levelized busbar cost of energy
- Initial capital cost of the system.

The hybrid system model is capable of sizing and simulating the performance of up to twenty different sizes of PV/wind or hydro hybrid combinations per run for a given load profile. The model can size and simulate any size combination ranging from an only PV and battery system to an only WECS or hydro and battery system. Exhibit 3-6 is a sample output of a PV/wind hybrid model run.

EXHIBIT 3-6

SAMPLE RUN - PV/WIND SIMULATOR

```
@XQT SYSTEM.
 ENTER TIME BASE FOR P/V SIZING
30
 ENTER PVEFF.PVCOST/KW.OMPV.LFPV.LFTPV.CEPV
.1 5000. .01 20 20 0.
 ENTER DCOEF.CCOEF,DDISCH.BATDPT.ETAB.COST/KW.OMBAT.LFBAT.LFTBAT.CEBAT.ND.EF INV
.25 .25 .7 50. .85 150. .01 10 10 0. 3 .85
 ENTER # OF WIND SYSTEMS. DERATING FRACTION
3 .85
 ENTER  3 LINES OF PR.VI.VR.VM.COST.O&M.MES.HGT.HUB HGT.LFWN.LFTWN.CEWN
0. 4. 11. 40. 0. 0. 10. 20. 20 20 0.
10. 4. 11. 40. 0120000. .025 10.20 20. 20 20 0.
20 4. 11. 40. 30000. .025 10. 20. 20 20 0.
 ENTER 3 LINES OF BOSCST.OMBOS.LFBOS.LFTBOS.CEBOS
1000. .01 20 20 0.
0. 0. 20 20 0.
3000. .01 20 20 0.
 ENTER RD. CD. RP. CP. RC. CCM. CI. CO. CT. CPI. CITC
1. .1 0. 0. 0. 0. 0. 0. 0. 0. 0.
 ENTER PROJECT LIFE. TAX LIFE
20 20
```

SYSTEM NUMBER	WIND MACHINE SIZE (KW)	PV ARRAY SIZE (SQ.M)	BATTERY SIZE (KWH)	LEVELIZED COST ($/KWH)	INITIAL COST ($)
1	.0000	.3097+03	.5858+03	.7649+00	.2767+06
2	.1000+02	.1489+03	.3540+03	.4635+00	.1655+06
3	.2000+02	.6935+02	.3458+03	.3666+00	.1265+06

```
SIMULATION ? (1=YES, 0=NO)

1


WHICH SYSTEM?
1


TOTAL ENERGY GENERATED
                    PV =   .64286+05 KWH
                  WIND =   .00000    KWH
                 TOTAL =   .64286+05 KWH

          TOTAL DEMAND =   .36719+05 KWH
  TOTAL ENERGY SURPLUS =   .15261+05 KWH ( 35.3% OF DEMAND)

        % OF DEMAND SATISFIED =  99.2 %
  % OF TIME DEMAND WAS SATISFIED =  99.0%
```

[NOTE: Instead of entering data during program execution, as shown above, it is more efficient to create a data file with the necessary data in the required order, and add it to the runstream.]

EXHIBIT 3-6 (CONCLUDED)

SAMPLE RUN - PV/WIND SIMULATOR

```
WHICH SYSTEM?
2



TOTAL ENERGY GENERATED
                     PV =  .30915+05 KWH
                   WIND =  .19912+05 KWH
                  TOTAL =  .50827+05 KWH

           TOTAL DEMAND =  .36719+05 KWH
  TOTAL ENERGY SURPLUS =  .47831+04 KWH ( 11.1% OF DEMAND)
  TOTAL ENERGY DEFICIT = .34178+03 KWH (    .8% OF DEMAND)

        % OF DEMAND SATISFIED =  99.2 %
% OF TIME DEMAND WAS SATISFIED =  98.6%



WHICH SYSTEM?
3



TOTAL ENERGY GENERATED
                     PV =  .14395+05 KWH
                   WIND =  .39824+05 KWH
                  TOTAL =  .54219+05 KWH

           TOTAL DEMAND =  .36719+05 KWH
  TOTAL ENERGY SURPLUS =  .73785+04 KWH ( 17.1% OF DEMAND)
  TOTAL ENERGY DEFICIT = .17618+03 KWH (    .4% OF DEMAND)

        % OF DEMAND SATISFIED =  99.6 %
% OF TIME DEMAND WAS SATISFIED =  99.2%



WHICH SYSTEM?
0

NORMAL EXIT.  EXECUTION TIME:       34644 MILLISECONDS.    STOP: 'END!
```

Input data variables needed for the run are described in Exhibit 3-7. The run also requires the following Fortran files to be assigned.

- File 7. Has 365 x 24 insolation values. This data was calculated by the stochastic hourly insolation generator.

- File 8. Has 365 x 24 wind speed or stream flow values. This data was calculated by the stochastic hourly wind speed generator or the hourly stream flow generator.

- File 9. Has 365 x 24 demand values. At present a program for generating the demand profile is not available; the data used in this analyses were developed using a text editor.

Sample output of files 7., 8. and 9. are shown in Exhibit 3-8. Note that if actual insolation, wind speed or streamflow data are available, then the stochastic generation of file 7. and 8. is not necessary. The hybrid system model requires approximately 10 CPU seconds to size, cost and simulate the performance over one year, of a PV/wind or hydro hybrid system.

3.2 PV/Engine Hybrid Model

Exhibit 3-9 shows the major components of the PV/engine hybrid model. This model can size, cost and simulate the performance of hybrid systems consisting of PV with diesel or gasoline generators, fuel cells, or CCVT. The components of the PV/engine model except for the following are identical to those of the PV/wind or hydro model:

- Engine performance model

- Hourly hybrid system performance simulation model.

The model using hourly insolation and demand profiles calculates the PV array and battery size needed to satisfy demand for a given engine size. Next it simulates the hourly performance of the hybrid system and calculates resource availability, levelized busbar costs and other parameters of interest as shown in Exhibit 3-9.

The PV/engine hybrid model has two operating protocols:

- Use energy generated by the PV array, if inadequate use the battery, if yet inadequate use the engine. If the PV array output is greater than demand, charge the battery. If battery is fully charged, dump excess energy.

- Use energy generated by the PV array, if inadequate use the engine, if yet inadequate use the battery. If PV output is greater than demand, charge battery. If battery is fully charged, dump energy.

EXHIBIT 3-7

INPUT DATA

ACRONYMS USED IN PV/WIND OR HYDRO SIMULATION MODELS

CARD	ACRONYM	DESCRIPTION
1.	TIME BASE FOR PV SIZING	= Any number of days from 1 to 365 ($1 \leq$ days ≤ 365)
2.	PVEFF	= Efficiency of PV Array (fraction)
	PVCOST/KW	= Array cost ($/kWp)
	OMPV	= Operation and maintenance cost per year as a fraction of initial capital cost of array (Fraction)
	LFPV	= Book of life PV array
	LFTPV	= Tax life of PV array (years)
	CEPV	= Cost escalation rate of PV array (fraction)
3.	DCOEF	= Maximum allowable discharge rate of battery as a fraction of battery capacity
	CCOEF	= Maximum allowable charge rate of battery (fraction)
	DDISCH	= Maximum allowable battery depth of discharge (fraction)
	BATDPT	= Initial state of charge of battery at the beginning of the simulation (percent)
	ETAB	= Overall battery efficiency (fraction)
	COST/KW	= Cost per kWh of storage ($/kWh)
	OMBAT	= Equivalent to OMPV
	LFBAT	= Equivalent to LFPV
	LFTBAT	= Equivalent to LFTPV
	CEBAT	= Equivalent to CEPV
	ND	= Number of days of storage required (days ≥ 0) (real)
	EFINV	= Inverter efficiency (fraction)
4.	# OF WIND/HYDRO SYSTEMS	= Number of WECS or hydroturbines for which data is supplied (Integer value >0 and < 20)
	DERATING FRAC.	= Fractional derated WECS output (fraction)
5.	(WIND) PR	= Rated WECS output (kW)
	VI	= Cut-in speed (m/s)
	VR	= Rated speed (m/s)
	VM	= Cut-out speed (m/s)
	COST	= Cost of WECS ($)
	O & M	= Equivalent to OMPV
	MES HGT	= Wind Spped Measurement height (m)
	HUB HGT	= Hub height of WECS (m)
	LFWN	= Equivalent to LFPV
	LFTWN	= Equivalent to LFTPV
	CEWN	= Equivalent to CEPV

EXHIBIT 3-7 (CONCLUDED)

INPUT DATA

(HYDRO) PR = Rated capacity of hydroturbine (kW)
HGT = Rated operating head (m)
COST = Cost of hydroturbine ($)
O&M = Equivalent to OMPV
LFWN = Equivalent to LFPV
LFTWN = Equivalent to LFTPV
CEWN = Equivalent to CEPV
FLO = Flow rate of water (m^3/sec)
[Note: FLO(1) = flow at minimum or cutin flow and FLO(5) = maximum or cutout flow]
EFF = Efficiency of turbine corresponding to FLO (fraction)

6. Data for the balance of system (BOS) components are entered here. The first row of data is for BOS associated with the PV arrays and cost is specified per kWp. The second row is for BOS associated with the WECS and cost is specified per kW of rated capacity. The last is for the joint BOS, where cost is specified as a dollar value for the joint BOS components.

BOSCST = Cost of BOS ($)
OMBOS = Equivalent to OMPV
LFBOS = Equivalent to LFPV
LFTBOS = Equivalent to LFTPV
CEBOS = Equivalent to CEPV

7. All of the following are all less than or equal to one

RD = Debt ratio
CD = Debt cost
RP = Preferred stock ratio
CP = Preferred stock cost
RC = Common stock ratio
CCM = Common stock cost
CI = Inflation rate
CO = O&M cost escalation rate
CT = Federal, state and local tax rate
CPI = Property tax and insurance rate
CITC = Investment tax credit

8. PROJECT LIFE = Book life of system (years)
TAX LIFE = System tax life (years)

EXHIBIT 3-8

INPUT DATA FILES TO BE ASSIGNED

*SAMPLE INSOLATION DATA USED IN MODEL (KW/M**2)

FILE 7

1	.00	.00	.00	.00	.00	.00	.00	.14	.46	.74	.89	.95	.89	.74	.46	.14	.00	.00	.00	.00	.00	.00	.00	.00
2	.00	.00	.00	.00	.00	.00	.00	.17	.56	.90	1.08	1.15	1.08	.90	.56	.17	.00	.00	.00	.00	.00	.00	.00	.00
3	.00	.00	.00	.00	.00	.00	.00	.15	.48	.77	.92	.98	.92	.77	.48	.15	.00	.00	.00	.00	.00	.00	.00	.00
4	.00	.00	.00	.00	.00	.00	.00	.19	.62	1.00	1.20	1.27	1.20	1.00	.62	.19	.00	.00	.00	.00	.00	.00	.00	.00
5	.00	.00	.00	.00	.00	.00	.00	.09	.30	.49	.59	.62	.59	.49	.30	.09	.00	.00	.00	.00	.00	.00	.00	.00
6	.00	.00	.00	.00	.00	.00	.00	.17	.54	.87	1.04	1.10	1.04	.87	.54	.17	.00	.00	.00	.00	.00	.00	.00	.00
7	.00	.00	.00	.00	.00	.00	.00	.11	.35	.56	.67	.71	.67	.56	.35	.11	.00	.00	.00	.00	.00	.00	.00	.00
8	.00	.00	.00	.00	.00	.00	.00	.16	.52	.83	.99	1.05	.99	.83	.52	.16	.00	.00	.00	.00	.00	.00	.00	.00
9	.00	.00	.00	.00	.00	.00	.00	.14	.44	.70	.84	.89	.84	.70	.44	.14	.00	.00	.00	.00	.00	.00	.00	.00
10	.00	.00	.00	.00	.00	.00	.00	.16	.50	.80	.95	1.01	.95	.80	.50	.16	.00	.00	.00	.00	.00	.00	.00	.00
365	.00	.00	.00	.00	.00	.00	.00	.14	.45	.73	.87	.93	.87	.73	.45	.14	.00	.00	.00	.00	.00	.00	.00	.00

*SAMPLE WIND SPEED DATA USED IN MODEL (M/SEC)

FILE 8

(For Hydro Simulation, Replace with Streamflow File)

1	6.4	1.6	4.2	2.2	10.5	6.9	5.8	2.2	5.5	1.9	6.2	5.8	3.2	1.2	1.9	1.1	5.9	2.9	4.6	2.7	2.6	.3	4.4	11.8
2	6.1	10.7	2.8	2.7	3.1	3.2	4.2	.8	1.3	1.0	1.4	.6	1.0	2.1	5.7	1.4	2.5	5.4	2.1	3.4	8.5	3.9	1.5	3.1
3	10.7	3.2	5.1	5.1	4.9	8.5	1.9	4.3	6.2	4.1	.4	.6	2.6	2.6	5.5	3.7	1.3	8.6	5.1	13.4	11.0	3.9	1.8	10.5
4	6.4	3.6	1.6	4.3	11.5	2.9	3.5	10.4	3.6	6.7	3.0	2.6	2.7	.9	9.6	5.2	2.2	2.1	2.4	4.9	5.7	5.9	6.0	2.5
5	5.1	3.8	5.0	3.1	4.9	3.7	8.9	1.9	4.0	2.8	5.0	3.5	2.6	1.5	4.2	2.7	5.3	4.3	2.5	2.6	1.1	5.9	6.9	2.3
6	2.7	2.7	3.5	7.2	3.5	2.9	6.0	7.2	.3	5.6	2.6	7.3	6.0	5.5	1.4	7.3	4.0	8.7	2.2	2.6	6.6	4.5	7.2	6.1
7	3.4	6.7	5.6	6.0	2.5	7.3	1.8	3.0	4.0	7.2	3.9	4.5	3.4	.1	4.1	1.7	4.7	7.8	3.4	2.4	2.3	7.0	1.7	3.9
8	3.2	4.6	5.1	.7	5.9	2.0	4.7	1.3	4.9	.4	2.8	1.5	2.9	1.6	3.7	1.7	1.8	4.4	3.5	6.3	7.8	2.4	.2	5.3
9	7.8	6.0	9.2	2.3	4.6	1.6	2.7	5.3	.7	2.5	2.4	3.8	5.9	4.8	6.3	.6	4.8	7.4	5.6	2.9	6.3	5.7	4.5	1.2
10	7.9	4.8	1.7	5.2	7.7	3.9	5.2	8.2	10.7	6.4	3.5	1.0	2.2	5.3	.7	10.8	3.1	3.5	5.4	.2	3.2	7.9	4.8	7.5
365	5.3	6.1	4.8	4.6	3.7	7.3	2.6	2.9	1.9	.8	3.6	1.2	1.1	5.3	5.6	5.3	2.1	6.5	2.8	5.5	3.8	2.9	4.7	10.3

*SAMPLE DEMAND PROFILE USED IN SIMULATION (KW)

FILE 9

.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29
.29	.29	.29	.29	.29	.29	.6	.6	.6	.6	.6	.6	.6	.6	.6	.6	.29	.29	.29	.29	.29	.29	.29	.29

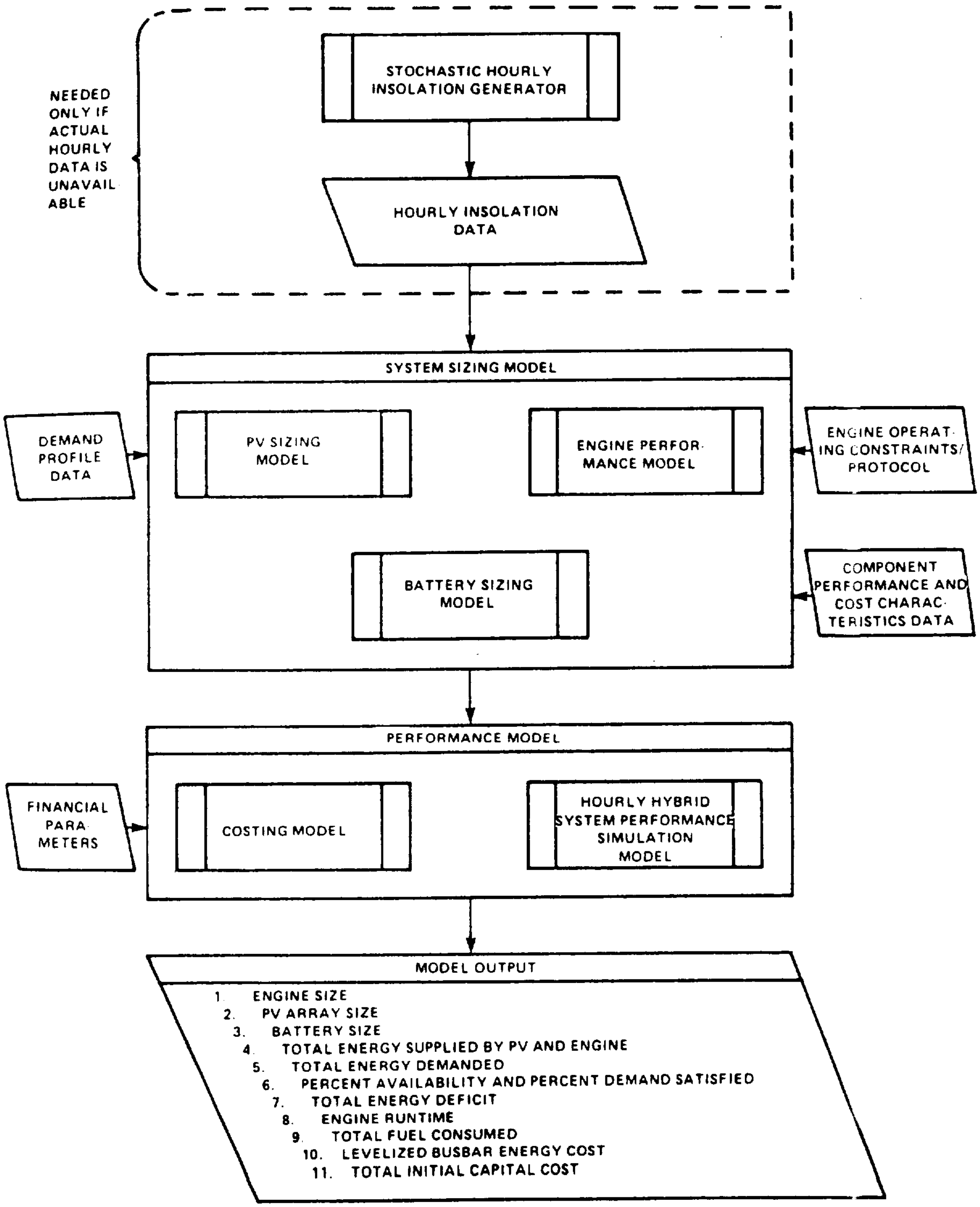


EXHIBIT 3-9: MAJOR COMPONENTS OF PV&DIESEL, GASOLINE, FUEL CELL OR CCVT MODEL

In the former case the engine is used for peaking power and the battery for intermediate power. In the latter case, the battery is used for peaking power.

The model can also specify several other operating conditions. They are:

1. Allows engine operating periods to be specified. For example, this enables engine to be used only at night, all day, or only as backup. This option is exercised by using the insolation levels to determine engine operating times.

2. Allows engine to charge the battery, if battery is at minimum state of charge.

3. Sets maximum and minimum engine operating capacity limits.

4. Allows engine to operate below minimum capacity with a user specified runtime penalty. This option is exercised when using diesels below about 50 percent capacity, since at low capacity factors, due to heavy carbonization, maintenance requirements increase.

5. Use of only the engine (no PV or battery)

6. Use of only the engine and battery (no PV)

7. Use of the engine, batteries and PV

8. Use of only PV and batteries.

The energy supplied from the engine is determined by the energy demanded subject to certain engine operating constraints and protocols. For example the engine may have to operate between upper and lower bounds which are less than maximum capacity and greater than zero respectively. For example, preferred operating range of diesels are 0.8 to 0.5 of maximum rated capacity. Engine fuel consumption is defined as a function of load. Manufacturers specifications are used to define the relationship between engine size, operating capacity and fuel consumption.

Exhibit 3-10 shows a sample run for the PV/engine model and Exhibit 3-11 describes the input data needed for model execution. The run requires two Fortran files to be assigned. They are:

- File 7. - Hourly insolation data

- File 9. - Hourly demand data.

Note that the current version of the PV/engine model requires that the hourly demand data include inverter losses; this model, unlike the PV/wind or hydro models does not internally adjust for inverter losses.

EXHIBIT 3-10

SAMPLE RUN OF PV/ENGINE MODEL

```
@XQT DIES.
 ENTER SOLLIM.SOLO.IONNPT.IONOPT.[illegible].NOPV.[illegible]
@ADD DSL100.
 ENTER NDIS.FC.CF.IPL.IPS.NBKUP
 ENTER  2 LINES OF CSIZ.DCOST.OMD.LFD.LFTD.CFD.CMIN.CMAX.CAPNOM,R(1)...[illegible]
 ENTER TIME BASE FOR PV SIZING
 ENTER PVEFF.PVCOST.OMPV.LFPV.LFTPV.CFPV
 ENTER DCOEF.CCOEF.DDISCH.BATDPT.ETAB.BATCST.OMBAT.LFBAT.LFTBAT.CFBAT.[illegible]INV
 ENTER 3 LINES OF BOSCST.OMBOS.LFBOS.LFTBOS.CFBOS
 ENTER RD.CD.RP.CP.RC.CCM.CI.CO.CT.CPT.CTTC
 ENTER LIFE.LTAX
```

DIES SIZE (KWP)	PV SIZE (M2)	BATTERY SIZE (KWH)	DIESEL ENERGY (KWH)	PV ENERGY (KWH)	TOTAL DEMAND (KWH)	% TIME SATSFIED	% DEM. SATSFIED	TOTAL DEFICIT (KWH)	TOTAL RUN TIME (HR)	TOTAL FUEL USED (GAL)	SYSTEM COST ($/KWH)	INITIAL COST ($)
3.0	.1491+03	.8616+02	.1754+05	.3096+05	.3672+05	.9997+02	.9993+02	.4792+01	.6315+04	.4001+04	.5417+00	.1266+06
6.0	.1413+03	.8719+02	.1864+05	.2933+05	.3672+05	.1000+03	.1000+03	.0000	.6033+04	.6016+04	.6314+00	.1290+06

```
NORMAL EXIT.  EXECUTION TIME:        14531 MILLISECONDS.


DATA 9R1 09/07/83-10:43 ANIL*DSL100(1)
    1.      0.  0.  0 0 1 0 1
    2.      2 1. 0. 0 0 0
    3.      3. 7250. .01 5 5 0. .25 1. 1. 0. .37 .37 .37 .37 1664.
    4.      6. 15000. .04 5 5 0. .25 1. 1. 0. .5 .5 .5 .5 3000.
    5.      30
    6.      .1 5000. .01 20 20 0.
    7.      .25 .25 .7 50. .85 150. .025 10 10 0. 1 .85
    8.      2000. .01 20 20 0.
    9.      0. .00 20 20 0.
   10.      2000. .01 20 20 0.
   11.      1. .05 0. 0. 0. 0. 0. 0. 0. 0. 0.
   12.      20 20
END DATA. ERRORS: NONE. TIME:  0.492 SEC. IMAGE COUNT: 12
```

EXHIBIT 3-11

INPUT DATA

ACRONYMS USED IN THE PV/ENGINE MODEL

CARD	ACRONYM		DESCRIPTION
1.	SOLLIM	=	Minimum value of insolation above which engine does not run, for sizing purposes
	SOLO	=	Same as above, for performance simulation [Note 1: If SOLLIM/SOLO equals zero, then engine operates only after sundown and before sunup. 2: If they are greater than about 10, then engine can operate all day, if needed. 3: If they are negative, then engine is used only in backup mode.]
			If the following variables are equal to one, then the corresponding options are enabled.
	IONNPT	=	Allows engine to charge battery if battery is at minimum allowable state of charge
	IONOPT	=	Allows engine to operate below an allowable minimum engine capacity
	IENBUP	=	Allows engine to be a backup to PV, overriding SOLO limit
	NOPV	=	Allows no PV, to test engine only case (note: if engine maximum allowable capacity is greater than peak demand, NOPV is redundant)
	IBTPK	=	Allows engine priority when insolation is less than SOLO
2.	NDIS	=	No. of engines for which data is given below
	FC	=	Fuel cost ($/unit)
	CF	=	Fuel cost escalation rate (fraction)
	IPL	=	Run time penalty for operating engine below allowable minimum engine capacity
	IPS	=	Run time penalty for engine cold start
	NBKUP	=	Number of backup engines used
3.	CSIZ	=	Rated capacity of engine (kW)
	DCOST	=	Engine cost ($)
	OMD	=	Operation and maintenance cost ($/hour of run time)
	LFD	=	Engine life (years)
	LFTD	=	Engine tax life (years)
	CED	=	Engine cost escalation rate (fraction)
	CMIN	=	Minimum allowable engine operating capacity as a fraction of rated capacity
	CMAX	=	Maximum allowable engine operating capacity as a fraction of rated capacity
	CAPNOM	=	Nominal engine plant factor (fraction)
	RR	=	Fuel consumption at idle and 25%, 50%, 75%, and 100% of rated capacity (units/hour)
	FMIN	=	Additional fuel consumption, if for example, a pilot light is needed (units/year)

EXHIBIT 3-11 (CONCLUDED)

INPUT DATA

ACRONYMS USED IN THE PV/ENGINE MODEL

4. Same as Card 1 for PV/Wind Model
5. Same as Card 2 for PV/Wind Model
6. Same as Card 3 of PV/Wind Model
7. Same as Card 6 for PV/Wind Model
8. Same as Card 7 for PV/Wind Model
9. Same as Card 8 for PV/Wind Model

The PV/engine model can size, cost and simulate up to twenty different engine sizes in one run. Model execution requires approximately seven CPU seconds to size, cost and simulate the performance of one PV/engine hybrid system.

4.0 PV HYBRID SYSTEMS EVALUATION

The purpose of this chapter is to present the analysis results obtained from the computer modeling of PV hybrid systems. The analyses will be used to select four PV hybrid systems for detailed conceptual design.

Six PV hybrid systems were investigated under three daily energy demand ranges. Exhibit 4-1 presents the types of power systems investigated under each of the demand ranges. The analysis was conducted using a load profile where 60 percent of the energy was used during the daytime hours (7 am to 5 pm). The ratio of maximum to minimum power demand was about two. A summary of the PV hybrid system configurations evaluated is shown in Exhibit 4-2. As mentioned in section 3.0, PV hybrid systems were divided into two categories: (1) PV/environmentally dependent source and (2) PV/fuel dependent source. Exhibit 4-3 shows the different operating protocols for both categories. The following costs have to be specified for system evaluation.

- Plant capital cost for each of the following:

  - PV array ($/$kW$_p$)
  - Balance of systems related to PV array ($/$kW$_p$)
  - Alternate generator ($)
  - Balance of systems related to alternate generator ($/Rated alternate generator capacity)
  - Battery ($/kWh of storage)
  - Balance of system for combined system ($)

- Fuel usage, if any, associated with each of the above hybrid system componets as a function of engine operating capacity.

- Operation and maintenance costs associated with each of the above hybrid system components. (specified as percent of capital costs for PV, wind, and hydropower generators and as $/hour of operation for diesel and gasoline generators, fuel cells and CCVT).

Since the systems had to be evaluated in a non-country specific manner, an economic analysis, rather than a financial analysis was used. Thus, taxes, credits, depreciation and related factors were not considered. All analyses were conducted in constant 1983 dollars and interest, escalation, discount and other rates were defined in real terms. Input data used in the analyses is presented in Appendix B.

The analysis judges the viability of the PV hybrid systems in terms of levelized busbar cost of energy and its availability. In this analysis, availability is defined as percent of time demand is satisfied given that the equipment is fully functional. Analyses in Section 5.0 will take into account the equipment reliability.

EXHIBIT 4-1

TYPES OF POWER SYSTEMS INVESTIGATED

TYPE	ENERGY DEMAND (KWH/DAY)		
	10	100	1000
1. PV/Wind	X	X	X
2. PV/Gasoline	X		
3. PV/Diesel		X	X
4. PV/Hydro		X	X
5. PV/Fuel Cell		X	
6. PV/CCVT	X		

EXHIBIT 4-2

SYSTEM CONFIGURATIONS EVALUATED

	TOTAL CONBINATIONS EVALUATED
1. PV/WIND	
• WITH 0,1, 3,5 DAYS OF BATTERY STORAGE	75
• WINTER PEAKING WIND SPEED & SUMMER PEAKING WIND SPEED	
• NIGHT PEAKING WIND SPEED & DAY PEAKING WIND SPEED	
• 0 KW THROUGH 500 KW WIND MACHINES (15 MACHINES)	
2. PV HYDRO	
• 1,2 & 3 MONTHS DROUGHT	12
• WINTER PEAKING FLOW	
• 0, 10 & 100 KW HYDRO TURBINES	
3. PV/DIESEL OR GASOLINE	
• ENGINE ALL DAY OPERATION	50
• ENGINE ONLY NIGHT-TIME OPERATION WITH BACKUP DURING DAY	
• ENGINE ONLY AS BACK-UP	
• USE OF BATTERY FOR PEAKING POWER	
• 0 KW THROUGH 75 KW (13 SIZES) GASOLINE AND DIESEL ENGINES	
4. PV/FUEL CELL	
• FUEL CELL OPERATING ALL DAY	20
• FUEL CELL NIGHT OPERATION WITH 1, 3&5 DAYS OF BATTERY STORAGE	
• FUEL CELL NIGHT OPERATION AND AS BACKUP (HOT STANDBY)	
• FUEL CELL NIGHT OPERATION AND AS BACKUP WHILE ALLOWED TO OPERATE BELOW LOWER CAPACITY LIMITS	
• USE OF BATTERY FOR PEAKING POWER	
• 0,3,6 KW FUEL CELLS	
5. PV/CCVT	
• CCVT ALL DAY OPERATION	24
• CCVT NIGHT OPERATION WITH 0,1,3,5 DAYS STORAGE	
• USE OF BATTERY FOR PEAKING POWER	
• 0 THROUGH 0.8 KW CCVTS	
6. PV ONLY	
• VARIATION OF RANDOM SEED IN GENERATING INSOLATION PROFILE	27
TOTAL CONFIGURATIONS	208

EXHIBIT 4-3

OPERATING PROTOCOLS OF THE HYBRID SYSTEMS

1. PV/Wind or Hydro Hybrid

Generates energy when resources are available and supplies power according to the following priorities:

1. Load
2. Battery
3. Dump excess energy

If supply is inadequate, battery supplies power, if yet inadequate, there is an energy deficit.

2. PV/Engine Hybrid

Protocol 1. Use energy generated by the PV Array, if inadequate use battery, if yet inadequate use engine. If PV Array output is greater than demand charge battery. If battery is fully charged, dump excess energy.

Protocol 2. Use energy generated by the PV Array, if inadequate use engine, if yet inadequate use battery. If PV output is greater than demand, charge battery. If battery is fully charged, dump energy.

The following options can be specified:

1. Allowable engine operating time (e.g., night, all day, only as backup).
2. Allow engine to charge battery, if battery is at minimum state of charge.
3. Allow engine to operate below minimum capacity with a user specified run-time penalty.
4. Use only the engine (no PV or battery).
5. Use only the engine and battery (no PV).
6. Use the engine, batteries and PV.
7. Use only PV and batteries.

4.1 PV Hybrid Systems for 10 kWh/Day Demand

Under this energy demand range, three PV hybrid systems were evaluated: (1) PV/wind (2) PV/gasoline engine, and (3) PV/CCVT. Since energy demand was low, to keep system complexity and cost low, the analysis assumed that DC power would be required. Exhibit 4-4 is a summary of the results obtained. A reference gasoline generator is used to compare each hybrid system to a conventional power generator. The underlined numbers indicate the hybrid combinations that appear to have the optimum low cost and high availability trade off.

4.1.1 PV/Wind System Evaluation

The following PV/wind hybrid systems were evaluated:

- PV/wind with no battery
- PV/wind with 1 day of battery storage
- PV/wind with 3 days of battery storage
- PV/wind with 5 days of battery storage

The wind profiles used (Appendix B) in this analysis had wind speeds peaking at night and in winter. Exhibits 4-5 shows the results obtained for the different PV/wind configurations tested. PV/wind with one day of battery storage (one day of battery storage equals the maximum energy required from the battery in any given day) is the best PV/wind combination because of its high availability and low cost. A plot of busbar cost and availability versus wind generator size is shown in Exhibit 4-6. All PV/wind hybrids have lower cost than a conventional stand-alone gasoline generator, making them feasible power sources. Due to the high cost/kW for a small wind generator, an increase in generator size causes an increase in cost.

The analysis shows that PV size decreases as wind generator size increases. The battery size initially decreases and then increases as wind generator increases. This effect could be due to the diurnal mismatch between demand and wind, and/or due to the higher variability of wind.

4.1.2 PV/Gasoline Engine System Evaluation

The following PV/gasoline generator hybrid systems were evaluated:

- Gasoline engine only
- PV/gasoline engine with engine allowed to operate all the time
- PV/gasoline engine with engine allowed to operate at night and as day time backup

EXHIBIT 4-4

RESULTS SUMMARY FOR 10KWH/DAY HYBRID SYSTEMS

HYBRID SYSTEM	LOWEST COST SYSTEM WITH RESOURCE AVAILABILITY ≥ 80%			HIGHEST RESOURCE AVAILABILITY SYSTEM WITH LOWEST COST		
	COST $/KWH	AVAIL-ABILITY %	PV SIZE (M^2)/ALT. SIZE (KW)	COST $/KWH	AVAIL-ABILITY %	PV SIZE (M^2)/ ALT. SIZE (KW)
WIND MACHINES						
1. With 1 Day Storage	0.46	96	18/0	0.55	99	10/1.2
2. With 3 Days Storage	0.53	98	18/0	.80	100	0/4
3. With 5 Days Storage	0.70	99	18/0	0.76	100	10/1.2
GASOLINE ENGINE						
1. All day operation	1.41	84	5/0.4	2.12	100	0/0.8
2. Night operation & as backup	0.93	94	10/0.4	1.42	100	10/0.8
3. Only as backup	0.52	97	18/0.3	0.56	100	18/0.4
4. Night operation, & battery for peak power	0.93	98	10/0.4	--	--	--
CCTV						
1. All day operation	2.82	84	3.5/0.4	4.40	100	0/0.8
2. Engine night use, 1 day storage	2.16	88	10/0.4	3.23	89	10/0.8
3. As in (2), 3 days storage	2.24	88	10/0.4	3.31	89	10/0.8
4. Night operation with 1 day battery for peaking power	2.05	98	10/0.4	--	--	--
PV ONLY						
1. With 1 day storage	0.46	96	18/0	--	--	--
2. With 3 days storage	0.53	98	18/0	--	--	--
3. With 5 days storage	0.70	99	18/0	--	--	--

*Reference Gasoline Generator Cost = $2.12/kWh

EXHIBIT 4-5

10 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	17.6	0	0	0.71	32.5	12270
	0	0	17.6	1	10.2	0.46	96.2	13840
	0	0	17.6	3	30.5	0.53	98.2	16880
	0	0	17.6	5	50.8	0.70	98.8	19920
PV/WIND WITH WIND PROFILE WINTER HIGH AND SUMMER LOW, NIGHT PEAKING	1.2	0	9.7	0	0	0.61	63.2	13520
	1.8	0	7.2	0	0	0.65	62.7	14010
	4.0	0	0	0	0	0.88	57.6	13700
same as above + 1 DAY OF BATTERY STORAGE	1.2	0	9.7	1	7.9	0.55	98.6	14810
	1.8	0	7.2	1	8.9	0.59	98.3	15420
	4.0	0	0	1	14.5	0.63	98.8	15810
same as above + 3 DAYS OF BATTERY STORAGE	1.2	0	9.7	3	23.8	0.66	99.4	17290
	1.8	0	7.2	3	26.8	0.70	99.3	18150
	4.0	0	0	3	43.5	0.80	99.5	19940
same as above + 5 DAYS OF BATTERY STORAGE	1.2	0	9.7	5	39.6	0.76	99.9	19770
	1.8	0	7.2	5	44.6	0.81	100.0	20890
	4.0	0	0	5	72.5	0.98	100.0	24060
DIESEL OR GASOLINE REFERENCE GENERATOR	0.8	1610	0	0	0	2.12	100.0	1870

* peak output 100 W/m^2
Input data in appendix B

*Reference Gasoline Generator Cost = $2.12/kWh

EXHIBIT 4-5 (CONCLUDED)

10 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	17.6	0	0	0.71	32.5	12270
	0	0	17.6	1	10.2	0.46	96.2	13840
	0	0	17.6	3	30.5	0.53	98.2	16880
	0	0	17.6	5	50.8	0.70	98.8	19920
PV/WIND WITH WIND PROFILE SUMMER HIGH AND WINTER LOW, NIGHT PEAKING	1.2	0	10.8	0	0	0.65	63.9	14190
	1.8	0	7.5	0	0	0.67	63.2	14240
	4.0	0	0	0	0	0.89	57.1	13700
same as above + 1 DAY OF BATTERY STORAGE	1.2	0	10.8	1	9.4	0.59	97.6	15660
	1.8	0	7.5	1	9.9	0.60	97.5	15780
	4.0	0	0	1	14.2	0.63	99.4	15770
same as above + 3 DAYS OF BATTERY STORAGE	1.2	0	10.8	3	28.1	0.71	98.5	18500
	1.8	0	7.5	3	29.8	0.73	98.4	18760
	4.0	0	0	3	42.5	0.79	99.7	19820
same as above + 5 DAYS OF BATTERY STORAGE	1.2	0	10.8	5	46.8	0.83	98.8	21340
	1.8	0	7.5	5	49.6	0.86	99.1	21740
	4.0	0	0	5	70.9	0.97	99.9	23860
DIESEL OR GASOLINE REFERENCE GENERATOR	0.8	1610	0	0	0	2.12	100.0	1870

* peak output 100 W/m^2

Input data in appendix B.

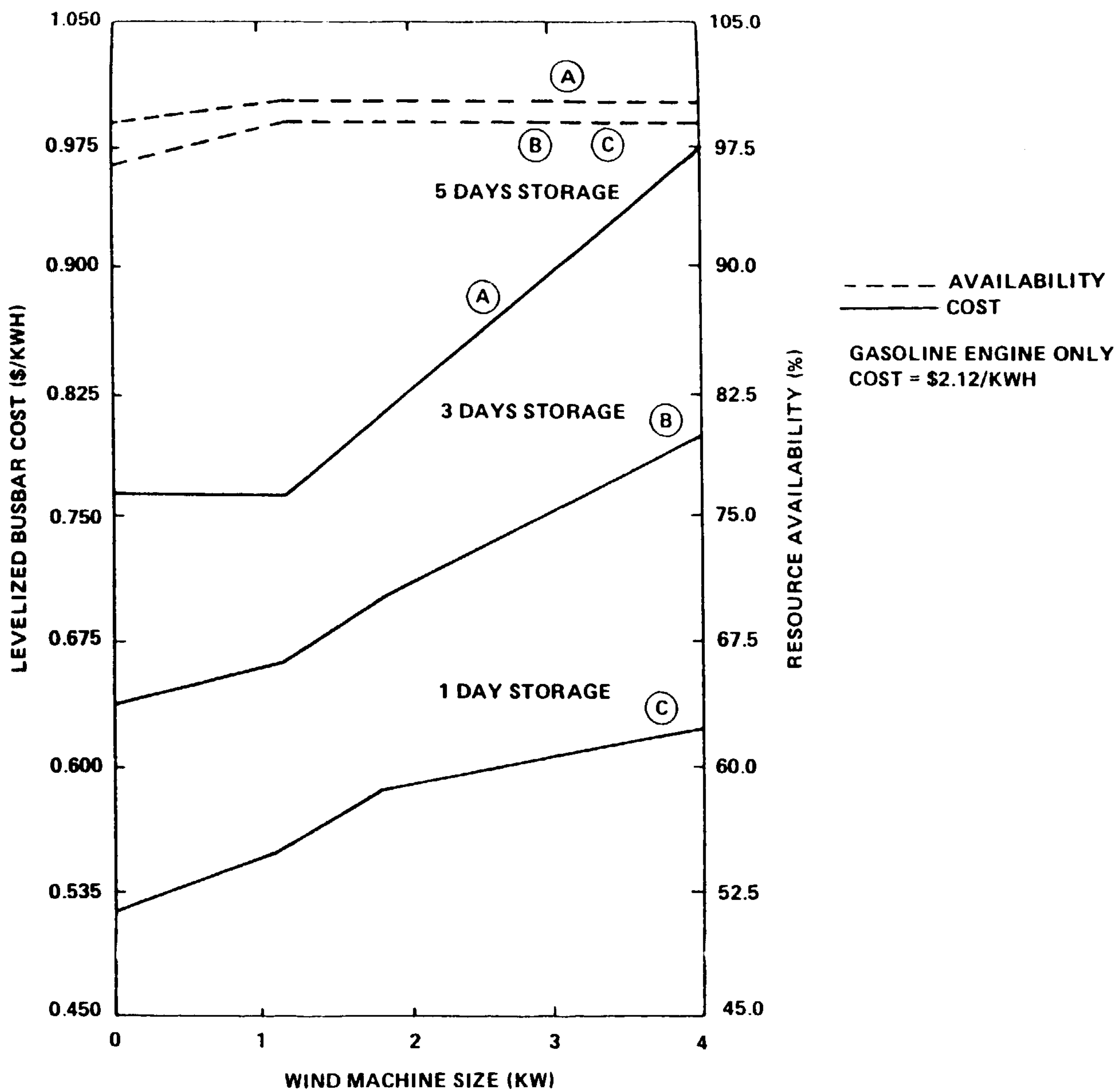


EXHIBIT 4-6: VARIATION OF COST & AVAILABILITY FOR 10 KWH/ DAY PV/WIND HYBRID SYSTEM

- PV/gasoline engine with engine used as backup only
- PV/gasoline engine with engine operating at night with battery used for peaking power.

All of the above hybrid systems used one day of battery storage. The results show that the least cost/high availability option is to use a 0.4 kW generator as a backup to the PV and battery. This configuration has lower cost than a stand-alone gasoline generator or even PV/battery with the similar high availability. The results are shown in Exhibit 4-7.

A comparison of items 2 and 4 in Exhibit 4-7 shows that a change in operating protocol (from using the engine for peaking power to using the battery for peaking power) for the same system configuration can cause a significant change in busbar cost and availability. In the latter case the engine is sized to handle the night time load, and since the battery will not be discharged during the night, it will have adequate stored energy for use during low insolation periods.

A graphical representation of the results is shown in Exhibit 4-8. The graph shows levelized busbar cost and availability versus engine size. The drop in availability for some configurations using smaller engine sizes is caused by deficiency in power during the early morning hours, and by the inability of the engine to satisfy peak power demands. As explained earlier this problem can be solved by using the battery for peaking power. Points X and Y in Exhibit 4-8 denote the cost and availability when the battery is used for peaking power.

All PV/gasoline hybrids have lower costs than a stand-alone gasoline engine making a PV/gasoline hybrid a more economical power system than a stand-alone gasoline generator. If the engine is used as a backup to a PV/battery system, it is more suitable in terms of low cost and very high availability than a PV only power system. However, using the engine only as a backup is not a true hybrid power system.

4.1.3 PV/CCVT System Evaluation

The following PV/CCVT hybrid systems were evaluated:

- CCVT engine only
- PV/CCVT with engine allowed to operate all the time
- PV/CCVT with engine operating at night
- PV/CCVT with engine operating at night plus 1 day of battery storage

EXHIBIT 4-7

10 kWh/DAY PV/GASOLINE HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gl)	PV * ARRAY * SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	17.6	0	0	0.71	32.5	12270
	0	0	17.6	1	10.2	0.46	96.2	13840
	0	0	17.6	3	30.5	0.53	98.2	16880
	0	0	17.6	5	50.8	0.70	98.8	19920
GASOLINE ENGINE ONLY	0.8	1610	0	0	0	2.12	100.0	1870
PV/GAS. WITH ENGINE OPERATING ALL THE TIME	0.3	640	7.5	1	4.2	1.17	35.5	6510
	0.4	895	4.9	1	2.7	1.41	83.7	4890
	0.8	1610	0	1	0	2.12	100.0	1870
PV/GAS. WITH ENGINE OPERATING AT NIGHT & AS DAYTIME BACKUP	0.3	344	11.3	1	6.3	0.84	63.7	9040
	0.4	486	10.1	1	5.7	0.93	94.0	8370
	0.8	739	10.1	1	5.7	1.42	100.0	8620
PV/GAS. WITH ENGINE OPERATING AS BACKUP ONLY	0.3	30	17.6	1	10.2	0.52	96.9	13310
	0.4	34	17.6	1	10.2	0.52	99.3	13450
	0.8	53	17.6	1	10.2	0.56	100.0	13710
PV/GAS. WITH ENGINE OPERATING AT NIGHT. ENGINE WITH OPERATING PRIORITY OVER BATTERY	0.4	529	10.1	1	5.7	0.93	98.2	8370

* peak output 100 W/m^2

Input data in appendix B

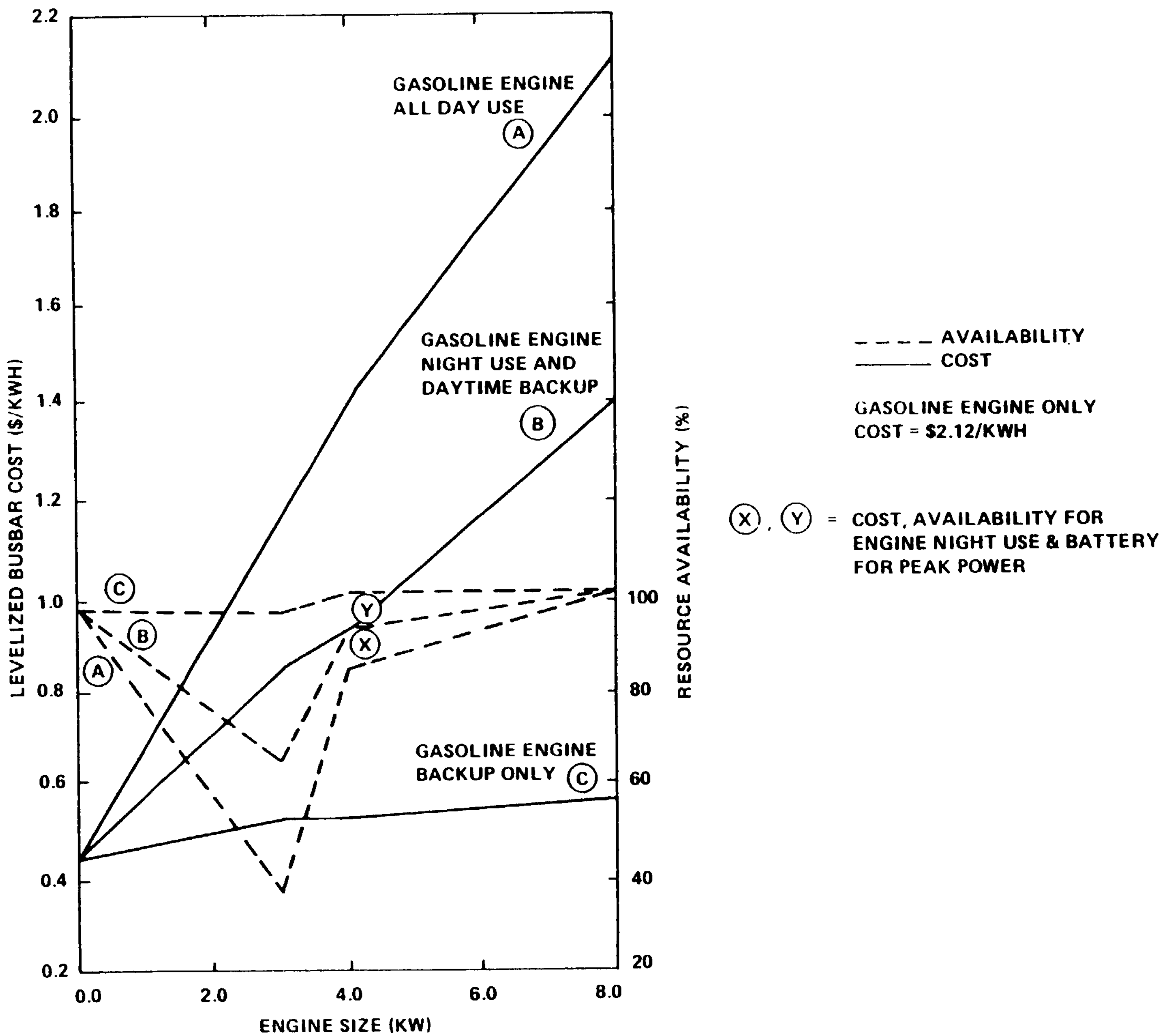


EXHIBIT 4-8: VARIATION OF COST & AVAILABILITY FOR 10 KWH/DAY PV/GASOLINE SYSTEM

- PV/CCVT with engine operating at night plus 3 days of battery storage
- PV/CCVT with engine operating at night plus 5 days of battery storage
- PV/CCVT with engine operating at night with battery for peaking power.

The results of the PV/CCVT hybrid analyses are shown in Exhibit 4-9. Plots of these results are shown in Exhibits 4-10 and 4-11.

The low cost hybrid option with highest availability would consist of the CCVT engine operating at night only with the battery used for peak power (the lowest cost alternative is to use only PV and batteries). This protocol has lower cost and higher availability for the same reasons given for the PV gasoline generator. A comparison of items 2 and 4 in Exhibit 4-9 shows this difference.

Exhibit 4-10 shows a plot of CCVT busbar cost versus engine size. It can be seen that any increase in engine size will increase cost. Point X is the cost when operating the engine at night with the battery used for peaking power. This hybrid configuration is the only PV/CCVT hybrid combination having both high availability, and a lower cost than a conventional gasoline generator. CCVT engine size versus availability is shown in Exhibit 4-11. Point Y is the availability corresponding to the point X cost in Exhibit 4-10.

As seen from the results, the PV/CCVT hybrid is more costly than the gasoline generator except for the case mentioned earlier. It is also more costly than the PV/battery power system. This makes PV/-CCVT hybrids marginal compared to the other possible hybrids. However, since a PV/CCVT hybrid has high equipment reliability and low O&M requirements, it is most suitable for remote unattended operations requiring very high reliability. In this demand range "PV/battery only" system is the lowest cost/high availability configuration. In areas with sufficient solar insolation a PV only power system is the least cost alternative.

4.2 PV Hybrid Systems for 100 kWh/day Demand

Under this demand range, four PV hybrid systems were evaluated: (1) PV/wind, (2) PV/diesel engine; (3) PV/hydro, and (4) PV/fuel cell. A summary of the results obtained is shown in Exhibit 4-12. A diesel engine stand-alone power system is used as a reference for cost and availability comparisons. The underlined numbers indicate the optimal hybrid combinations in terms of low cost and high availability.

EXHIBIT 4-9

10 kWh/DAY PV/CCVT HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (LB)	PV * ARRAY * SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	17.6	0	0	0.71	32.5	12270
	0	0	17.6	1	10.2	0.46	96.2	13840
	0	0	17.6	3	30.5	0.53	98.2	16880
	0	0	17.6	5	50.8	0.70	98.8	19920
CCVT ENGINE ONLY	0.8	25000	7.2	0	0	4.40	100.0	31170
PV/CCVT WITH ENGINE OPERATING ALL THE TIME	0.2	4209	9.2	1	5.1	1.90	45.5	24040
	0.4	12728	3.5	1	1.9	2.82	83.7	27010
	0.8	25000	0	1	0	4.40	100.0	31170
PV/CCVT WITH ENGINE OPERATING AT NIGHT	0.2	3894	12.4	0	0	2.31	27.5	25920
	0.4	7321	10.1	0	0	1.99	79.4	30550
	0.8	14178	10.1	0	0	4.10	80.6	37050
PV/CCVT WITH ENGINE OPERATING AT NIGHT + 1 DAY BATTERY	0.2	2070	12.4	1	6.8	1.52	67.7	26950
	0.4	5651	10.1	1	5.7	2.16	88.1	31430
	0.8	10838	10.1	1	5.7	3.23	88.9	29920
PV/CCVT WITH ENGINE OPERATING AT NIGHT, ENGINE WITH OPERATING PRIORITY OVER BATTERY	0.4	7321	10.1	1	5.7	2.00	98.4	31430
DIESEL OR GASOLINE REFERENCE GENERATOR	0.8	1610 (gl)	0	0	0	2.12	100.0	1870

* peak output 100 W/m^2

Input data in appendix B

EXHIBIT 4-9 (CONCLUDED)

10 kWh/DAY PV/CCVT HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (LB)	PV * ARRAY * SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV/CCVT WITH ENGINE OPERATING AT NIGHT + 3 DAY BATTERY	0.2 0.4 0.8	2065 5642 10828	12.4 10.1 10.1	3 3 3	20.5 17.0 17.0	1.63 2.24 3.31	67.8 88.1 89.0	28990 33180 39680
PV/CCVT WITH ENGINE OPERATING AT NIGHT + 5 DAY BATTERY	0.2 0.4 0.8	2059 5633 10808	12.4 10.1 10.1	5 5 5	34.2 28.3 28.3	1.74 2.33 3.39	67.9 88.1 89.0	31040 34940 41430
PV/CCVT WITH ENGINE OPERATING AT NIGHT + 1 DAY BATTERY, 10 DAY SIZING PERIOD	0 0.2 0.4 0.8	0 1533 4876 10052	19.7 13.8 10.9 10.6	1 1 1 1	9.6 6.3 5.2 5.4	0.50 1.36 2.03 3.08	98.3 77.4 89.3 89.8	13710 27730 31890 38330
PV/CCVT WITH ENGINE OPERATING AT NIGHT + 10 DAY BATTERY 5 DAY SIZING PERIOD	0 0.2 0.4 0.8	0 987 3997 7611	21.5 15.1 12.0 11.9	10 10 10 10	97.7 57.3 47.3 47.5	1.69 2.24 2.93 3.71	100.0 89.1 90.2 91.0	47120 56220 59100 65600
DIESEL OR GASOLINE REFERENCE GENERATOR	0.8	1610 (gl)	0	0	0	2.12	100.0	1870

* peak output 100 W/m^2

Input data in appendix B

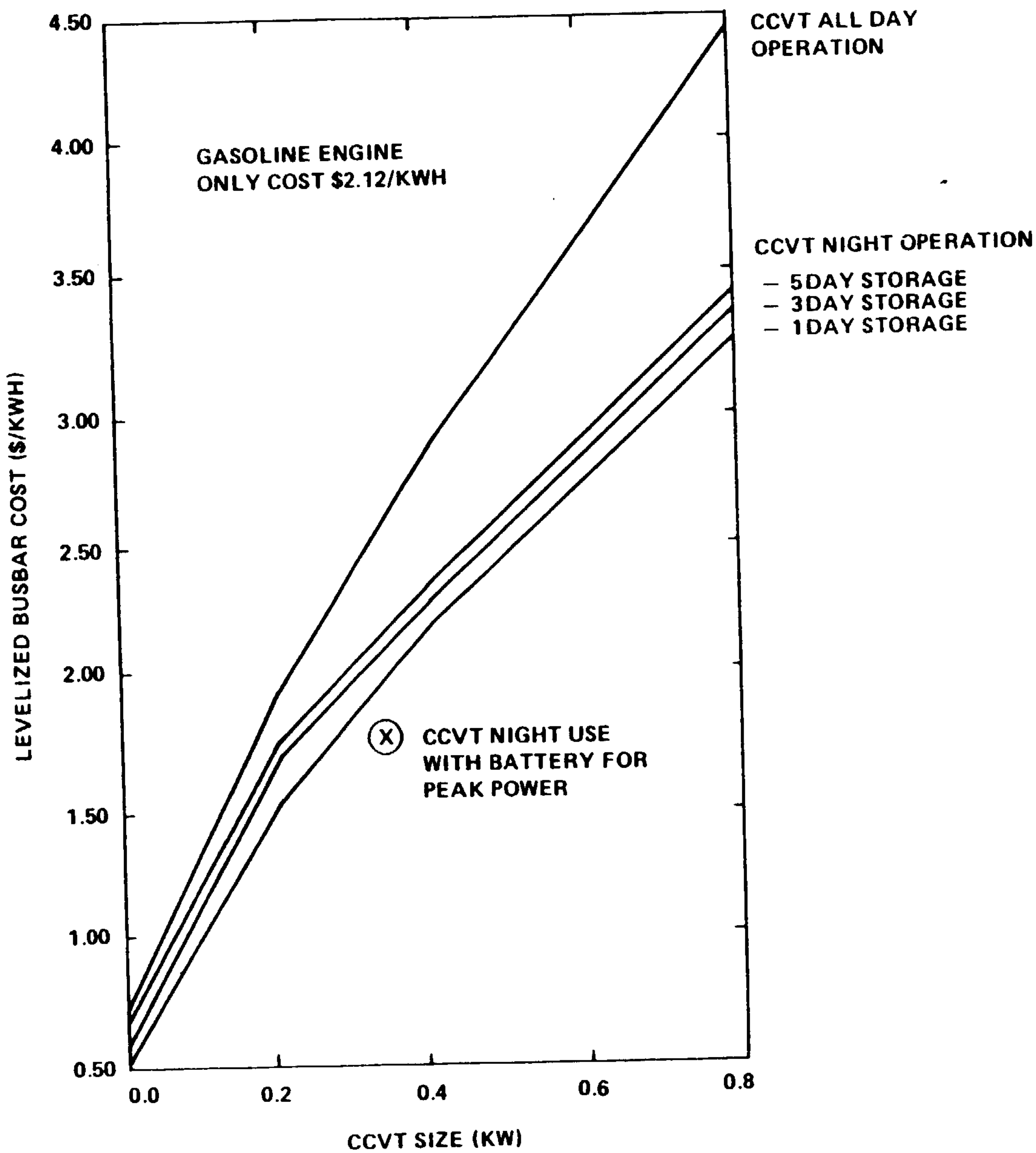


EXHIBIT 4-10: VARIATION OF COST FOR 10 KWH/DAY PV/CCVT HYBRID SYSTEM

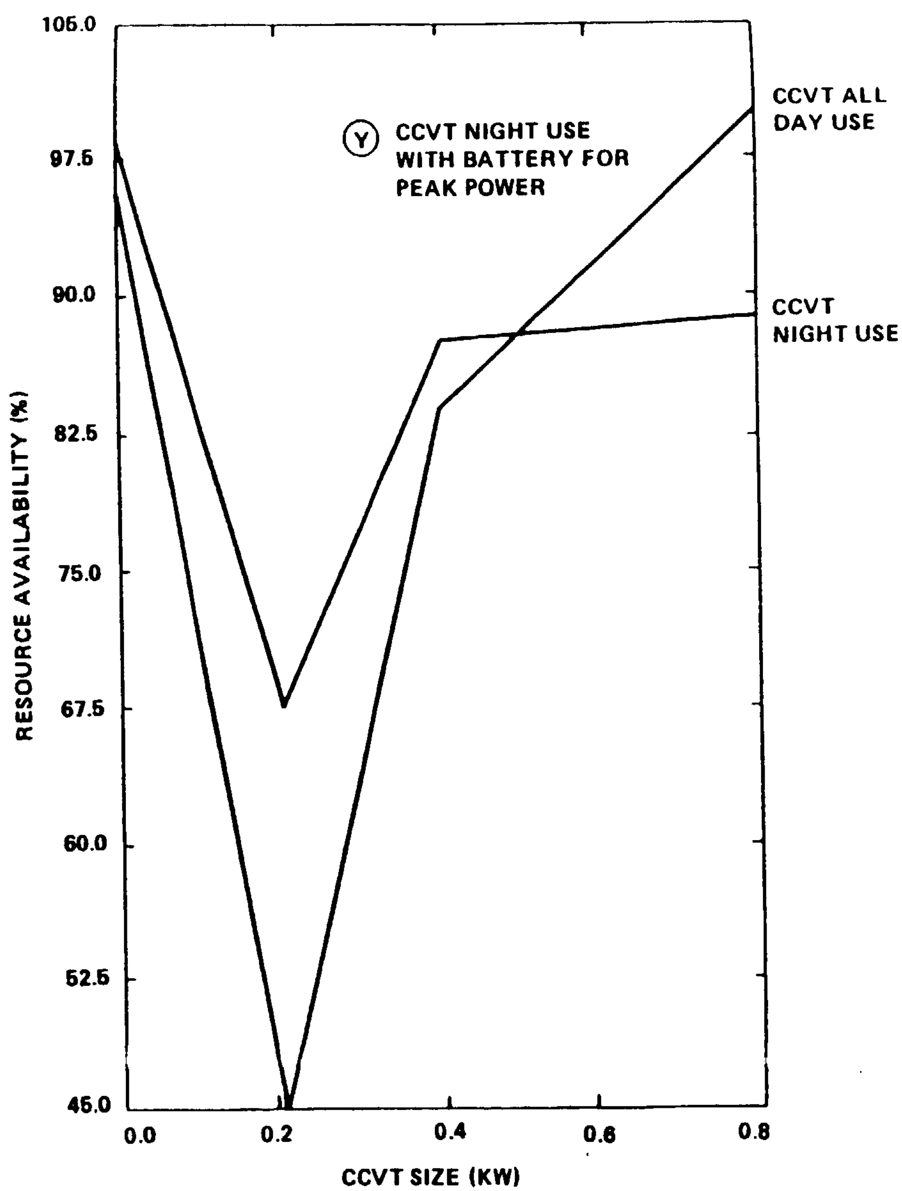


EXHIBIT 4-11: VARIATION OF COST FOR 10 KWH/DAY PV/CCVT HYBRID SYSTEM

EXHIBIT 4-12

RESULTS SUMMARY FOR 100 kWh/DAY HYBRID SYSTEMS

HYBRID SYSTEM	LOWEST COST SYSTEM WITH RESOURCE AVAILABILITY ≥ 80%			HIGHEST RESOURCE AVAILABILITY SYSTEM WITH LOWEST COST		
	COST $/KWH	AVAIL-ABILITY	PV SIZE (M^2)/ALT. SIZE (KW)	COST $/KWH	AVAIL-ABILITY	PV SIZE (M^2)/ALT. SIZE (KW)
WIND MACHINES						
1. With 1 Day Storage	0.36	98	42/25	0.45	99	105/10
2. With 3 Days Storage	0.52	99	42/25	0.57	99	105/10
3. With 5 Days Storage	0.65	100	84/15	0.65	100	84/15
DIESEL ENGINE						
1. All day operation	0.49	100	0/9	0.49	100	0/9
2. Night Operation & as Backup	0.55	94	101/4	0.67	100	101/9
3. Only as backup	0.59	97	176/3	0.63	100	176/9
4. Night operation, with battery for peak power	0.55	98	101/4			
HYDRO TURBINE						
1. No drought; adequate flow	0.19	100	0/10	--	--	--
2. 2 month drought	0.70	99	145/10	--	--	--
3. 3 month drought	0.71	98	147/10	0.75	99	167/10
4. Winter peaking Flow	0.56	[illegible]	91/10	--	--	--
FUEL CELLS						
1. All day operation	0.53	100	0/6	0.53	100	0/6
2. Night operation 1 day storage	0.49	87	101/3	0.49	87	101/6
3. Night operation & backup	0.64	96	101/6	0.64	96	101/6
4. Night operation, backup and lower limit zero	0.65	100	101/6	0.65	100	101/6
5. Night operation with battery (1 day storage) for peak-	0.48	98	101/3			

REFERENCE: DIESEL GENERATOR - COST - $0.49/KWH

4.2.1 PV/Wind System Evaluation

Four PV/wind system configurations were evaluated with three different levels of battery storage. They were the following:

- PV/wind with no battery storage
- PV/wind with 1 day of battery storage
- PV/wind with 3 days of battery storage
- PV/wind with 5 days of battery storage.

Exhibits 4-13 and 4-14 show the results obtained for these PV/wind systems. For this set of evaluations a wind profile with wind speed peaking during the winter months was used. In this wind machine size range, an increase in wind machine size results in a decrease in cost, with availability remaining almost constant. It is important to note that as the wind machine size increases, the size of the battery increases because of the greater variability of wind as compared to solar insolation. For larger amounts of battery storage, as seen in Exhibit 4-14 for the 5 days of battery storage case, an increase in battery size causes a significant increase in cost.

A second set of evaluations was done for exactly the same PV/wind system. This evaluation used a wind profile with wind speeds peaking during the summer months and at night. The results are shown in Exhibit 4-15. To evaluate the effect of changing the daily wind profile from wind speed peaking at night to wind speed peaking during day time, the performance of two PV/wind configurations was examined. The results are shown in Exhibit 4-16. It can be seen that a change in daily wind profile does not cause a significant change in battery size, PV array size, cost, or availability. The reason for this is that the battery acting as a buffer smoothes the power output on a diurnal basis. It will be shown later that the same is not true for a seasonal variation of wind speed profile.

The effect of wind speed magnitude on cost and availability was also evaluated and the results are shown in Exhibit 4-17. It was found, as expected, that an increase in wind speed favors use of larger wind machines with a corresponding reduction in array size. The reduction in array size and cost is considerable; it shows that if there are good wind resources, there is no need for a PV array.

The results of a variation of wind speed profile on a seasonal basis are shown graphically in Exhibit 4-18. The graph shows the effect of this change on PV array and battery size as wind machine size increases. It shows that a summer peaking wind profile will significantly increase both the PV array and battery sizes to make up for the reduction of wind resources during the winter. Exhibit 4-19 shows the effect of seasonal variations of wind on cost and availability. Again because of the need for a larger PV array and battery, the cost to provide the same amount of energy increases when both

EXHIBIT 4-13

100 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS

RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	176.2	0	0	0.88	32.5	115700
	0	0	176.2	1	101.5	0.56	96.2	133400
	0	0	176.2	3	304.5	0.72	98.2	162800
	0	0	176.2	5	507.5	0.86	98.8	190200
PV/WIND WITH WIND PROFILE WINTER HIGH AND SUMMER LOW, NIGHT PEAKING	4.0	0	130.5	0	0	0.56	48.5	98680
	10.0	0	105.3	0	0	0.47	61.5	90190
	15.0	0	84.4	0	0	0.42	64.0	80110
	25.0	0	42.4	0	0	0.35	55.9	60460
same as above + 1 DAY OF BATTERY STORAGE	4.0	0	130.5	1	78.5	0.49	97.9	113400
	10.0	0	105.3	1	78.3	0.45	98.7	105000
	15.0	0	84.4	1	82.1	0.41	98.5	95380
	25.0	0	42.4	1	112.5	0.36	98.0	79520
same as above + 3 DAYS OF BATTERY STORAGE	4.0	0	130.5	3	235.6	0.60	99.0	137100
	10.0	0	105.3	3	234.8	0.57	99.4	128500
	15.0	0	84.4	3	246.3	0.54	99.3	119900
	25.0	0	42.4	3	337.4	0.52	99.0	111600
same as above + 5 DAYS OF BATTERY STORAGE	4.0	0	130.5	5	392.7	0.71	99.5	158800
	10.0	0	105.3	5	391.3	0.68	99.9	150100
	15.0	0	84.4	5	410.5	0.65	100.0	142400
	25.0	0	42.4	5	562.3	0.67	99.7	141700
DIESEL OR GASOLINE REFERENCE GENERATOR	9.0	5070	0	0	0	0.49	100.0	21000

* peak output 100 W/m^2

Input data in appendix B.

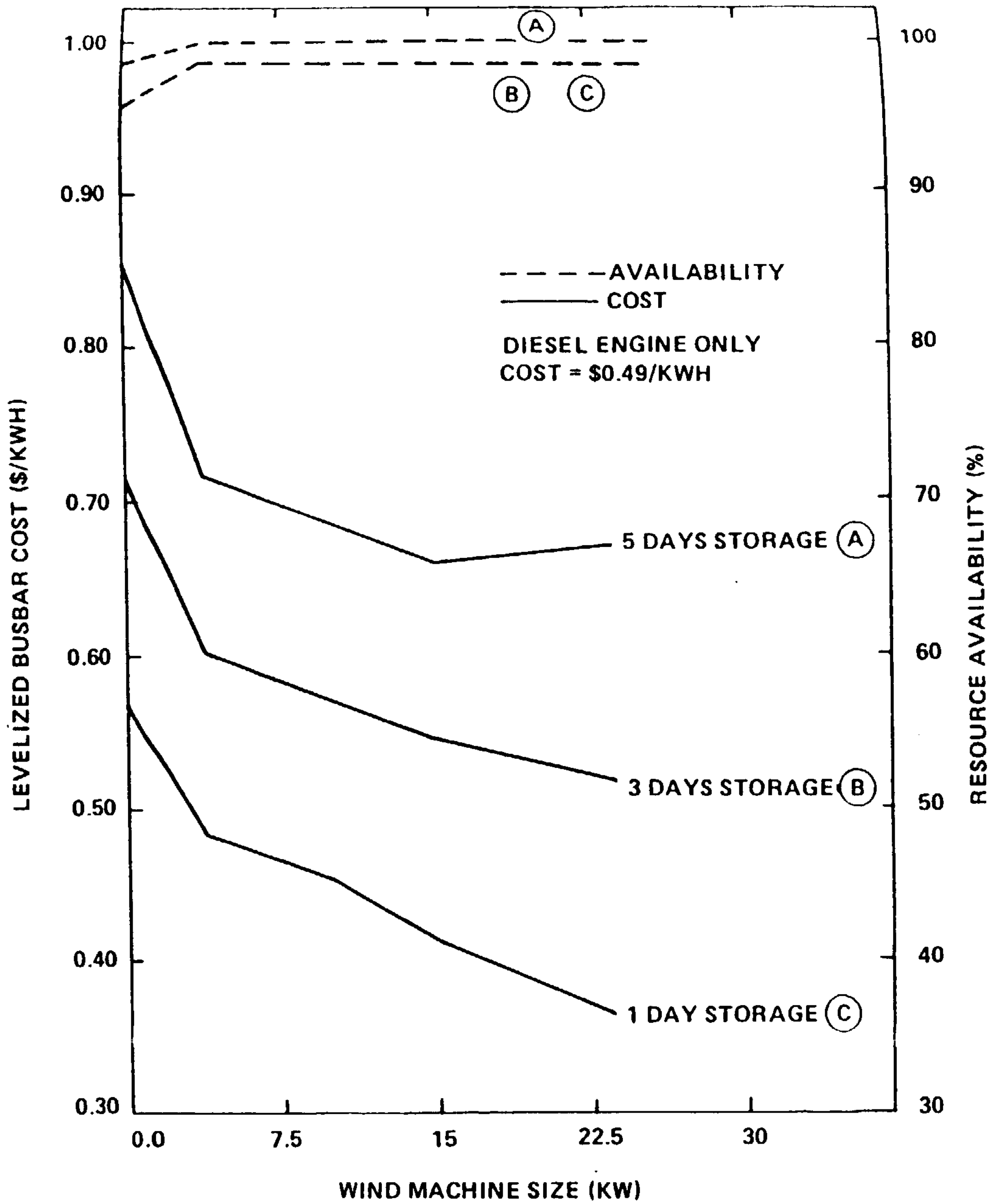


EXHIBIT 4-14: COST AND AVAILABILITY FOR 100 KWH/DAY PV/WIND HYBRID SYSTEM

EXHIBIT 4-15

100 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS RESULTS FOR SUMMER PEAKING WIND SPEEDS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	176.2	0	0	0.88	32.5	115700
	0	0	176.2	1	101.5	0.56	96.2	133400
	0	0	176.2	3	304.5	0.72	98.2	162800
	0	0	176.2	5	507.5	0.86	98.8	190200
PV/WIND WITH WIND PROFILE SUMMER HIGH AND WINTER LOW, NIGHT PEAKING	4.0	0	153.5	0	0	0.63	50.8	112500
	10.0	0	119.5	0	0	0.52	62.8	98710
	15.0	0	91.8	0	0	0.44	64.5	84570
	25.0	0	72.8	0	0	0.35	54.8	57700
same as above + 1 DAY OF BATTERY STORAGE	4.0	0	153.5	1	91.1	0.56	97.5	128900
	10.0	0	119.5	1	91.8	0.50	97.6	115200
	15.0	0	91.8	1	96.1	0.45	97.6	101600
	25.0	0	37.8	1	113.6	0.35	97.3	76900
same as above + 3 DAYS OF BATTERY STORAGE	4.0	0	153.5	3	273.3	0.69	98.6	155700
	10.0	0	119.5	3	275.4	0.64	98.5	142100
	15.0	0	91.8	3	288.2	0.59	98.5	129600
	25.0	0	37.8	3	340.9	0.51	98.1	109300
same as above + 5 DAYS OF BATTERY STORAGE	4.0	0	153.5	5	455.5	0.82	99.2	180500
	10.0	0	119.5	5	459.0	0.76	98.9	167100
	15.0	0	91.8	5	480.3	0.72	99.1	155600
	25.0	0	37.8	5	568.1	0.67	99.0	139700
DIESEL OR GASOLINE REFERENCE GENERATOR	9.0	5070	0	0	0	0.49	100.0	21000

* peak output 100 W/m^2

Input data in appendix B.

EXHIBIT 4-16

100 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS RESULTS

FOR DAYTIME PEAKING WIND SPEEDS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	176.2	0	0	0.88	32.5	115700
	0	0	176.2	1	101.5	0.56	96.2	133400
	0	0	176.2	3	304.5	0.72	98.2	162800
	0	0	176.2	5	507.5	0.86	98.8	190200
PV/WIND WITH WIND PROFILE WINTER HIGH AND SUMMER LOW, DAY PEAKING	4.0	0	129.3	0	0	0.61	40.4	97960
	10.0	0	102.3	0	0	0.51	51.5	88380
	15.0	0	79.8	0	0	0.44	54.7	77400
	25.0	0	34.9	0	0	0.34	54.6	55940
same as above + 1 DAY OF BATTERY STORAGE	4.0	0	129.5	1	77.7	0.48	97.4	112700
	10.0	0	102.3	1	76.2	0.44	98.4	102900
	15.0	0	79.8	1	79.0	0.40	98.4	92270
	25.0	0	34.9	1	101.3	0.33	97.9	73600
DIESEL OR GASOLINE REFERENCE GENERATOR	9.0	5070	0	0	0	0.49	100.0	21000

* peak output 100 W/m^2

Input data in appendix B.

EXHIBIT 4-17

100 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS RESULTS FOR HIGH WINDSPEED REGIONS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	176.2	0	0	0.88	32.5	115700
	0	0	176.2	1	101.5	0.56	96.2	133400
	0	0	176.2	3	304.5	0.72	98.2	162800
	0	0	176.2	5	507.5	0.86	98.8	190200
PV/WIND WITH WIND PROFILE WINTER HIGH AND SUMMER LOW, MAX SPEED 16 m/s NIGHT PEAKING MAX SPEED 16 m/s	4.0	0	86.4	1	54.8	0.36	99.1	84120
	10.0	0	0	1	109.7	0.21	99.4	45710
	15.0	0	0	1	101.9	0.22	100.0	47240
	25.0	0	0	1	90.5	0.23	100.0	51310
same as above with SEASONAL MAX SPEED OF 10 m/s AND MAX NIGHT SPEED OF 15 m/s	4.0	0	122.4	1	75.7	0.47	97.8	108300
	10.0	0	87.9	1	74.4	0.41	98.9	94060
	15.0	0	59.2	1	90.3	0.36	98.7	81310
	25.0	0	1.8	1	134.3	0.27	98.5	57850
DIESEL OR GASOLINE REFERENCE GENERATOR	9.0	5070	0	0	0	0.49	100.0	21000

* peak output 100 W/m^2

Input data in appendix B.

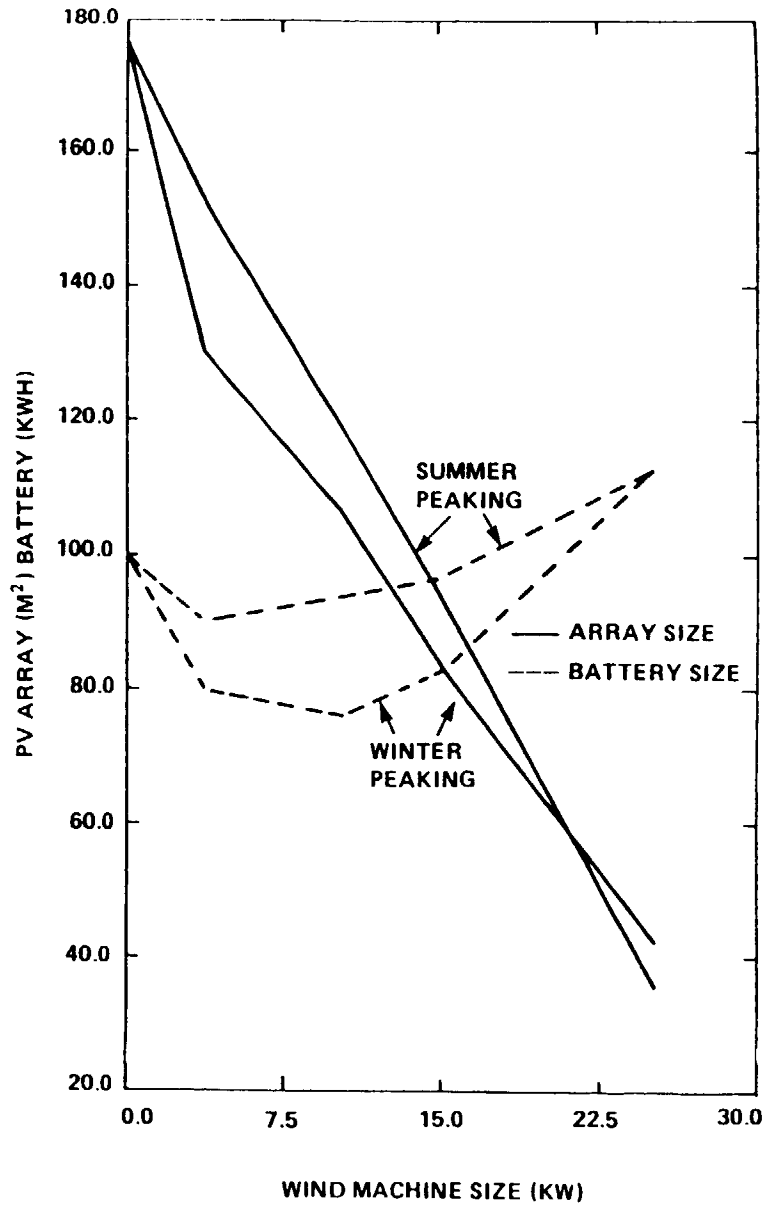


EXHIBIT 4-18: EFFECT OF SEASONAL PEAKING OF WINDSPEED ON SYSTEM COMPONENT SIZES FOR 100 KWH/DAY PV/WIND HYBRID SYSTEM

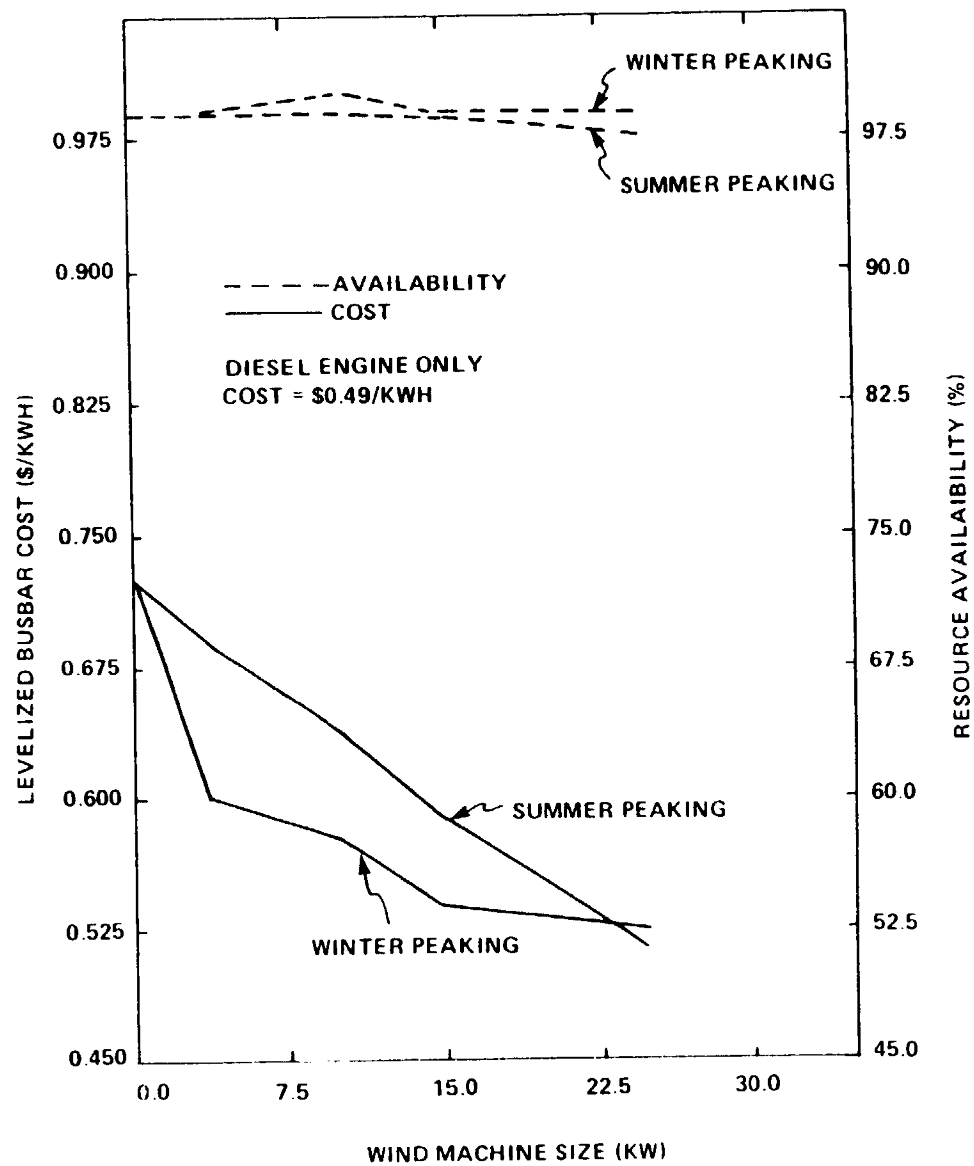


EXHIBIT 4-19: EFFECTS OF SEASONAL PEAKING OF WIND FOR 100 KWH/DAY PV/WIND HYBRID SYSTEM

resources are peaking during the same season. The availability also drops for the summer peaking wind profile. It can be seen that a seasonal variation of wind speed has a major effect on system performance and cost.

The effect of varying the cost of PV and battery was evaluated for the minimum cost PV/wind hybrid. Tabulated results, presented in Exhibit 4-20, show that the cost is slightly more sensitive to changes in battery cost than to changes in array cost.

4.2.2 PV/Diesel Engine Evaluation

Five PV/diesel hybrid configurations were evaluated, they are:

- Diesel engine only
- PV/diesel with engine allowed to operate all the time
- PV/diesel with engine operating at night and as daytime backup
- PV/diesel with engine operating as backup only
- PV/diesel with engine operating at night with battery used for peaking power.

All the above hybrids have one day of battery storage. The results of this hybrid system evaluation are shown in Exhibit 4-21. It was found that the lowest cost PV/diesel hybrid with high availability resulted when the engine was used at night only with a battery for peaking power. However, unlike the CCVT case, the cost and availability differences were not as significant. The results show that none of the PV/diesel hybrids have a cost lower than a stand-alone diesel generator. But, the cost differential was not very large. Given the expected high equipment reliabilities of PV arrays when compared to diesels, on an operational availability basis, a PV/diesel might be preferable for some remote applications. A graphical representation of these results is shown in Exhibit 4-22. The graph shows cost and availability versus diesel engine size. The drop in availability at small engine sizes occurs for the same reason given for the smaller PV/gasoline generator hybrid system. Point X and Y on Exhibit 4-22 represent the cost and availability of a PV/diesel system with the diesel engine operating at night and as a backup, with the battery used for peaking power.

To test the cost sensitivity for changes in fuel cost for different engine operating protocols, eight cases were evaluated. The results are shown in Exhibit 4-23. As expected, fuel cost has a significant effect on busbar cost when the diesel engine is used a large percent of the time. Even though biogas cost is not truly zero, it is used as zero to test the case where marginal fuel cost may be zero.

EXHIBIT 4-20

EFFECT OF ARRAY & BATTERY COST VARIATIONS ON ENERGY COSTS FOR MINIMUM COST PV/WIND 100 kWh/DAY HYBRID SYSTEMS

		PV ARRAY COSTS		PERCENT CHANGE IN ENERGY COSTS FOR A ONE PERCENT CHANGE IN ARRAY COSTS
		$3000/kWp	$5000/kWp	
BATTERY COSTS	$150/kWh	$.485/kWh WIND = 15 kW PV = 84.4 M^2 BATT = 246.3 kWh	$.565/kWh WIND = 25 kW PV = 42.4 M^2 BATT = 337.4 kWh	0.354
	$125/kWh	$.453/kWh WIND = 15 kW PV = 84.4 M^2 BATT = 246.3 kWh	$.520/kWh WIND = 25 kW PV = 42.4 M^2 BATT = 337.4 kWh	0.322
PERCENT CHANGE IN ENERGY COSTS FOR A ONE PERCENT CHANGE IN BATTERY COSTS		0.353	0.433	

EXHIBIT 4-21

100 kWh/DAY PV/DIESEL HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	176.2	0	0	0.88	32.5	115700
	0	0	176.2	1	101.5	0.56	96.2	133400
	0	0	176.2	3	304.5	0.72	98.2	162800
	0	0	176.2	5	507.5	0.86	98.8	190200
DIESEL ENGINE ONLY	9.0	5070	0	0	0	0.49	100.0	21000
PV/DIESEL WITH ENGINE OPERATING ALL THE TIME	3.0	1978	75.3	1	41.6	0.56	35.5	75450
	4.0	3119	49.1	1	27.1	0.57	83.7	59620
	6.0	4081	21.0	1	11.6	0.55	83.7	44320
	9.0	5070	0	1	0	0.49	100.0	21000
PV/DIESEL WITH ENGINE OPERATING AT NIGHT AND AS DAYTIME BACKUP	3.0	1128	113.2	1	62.5	0.56	63.7	100800
	4.0	1690	100.9	1	56.5	0.55	94.0	94410
	6.0	1985	100.8	1	56.6	0.58	96.5	97820
	9.0	2398	100.8	1	56.6	0.67	100.0	101500
PV/DIESEL WITH OPERATING AS BACKUP ONLY	3.0	97	176.2	1	105.5	0.59	96.9	143500
	4.0	118	176.2	1	105.5	0.60	99.3	145200
	6.0	141	176.2	1	105.5	0.62	99.6	148700
	9.0	171	176.2	1	105.5	0.63	100.0	152400
PV/DIESEL WITH ENGINE OPERATING AT NIGHT, ENGINE WITH OPERATING PRIORITY OVER BATTERY	4.0	1832	100.1	1	56.5	0.55	98.2	94410

* peak output 100 W/m^2
Input data in appendix B.

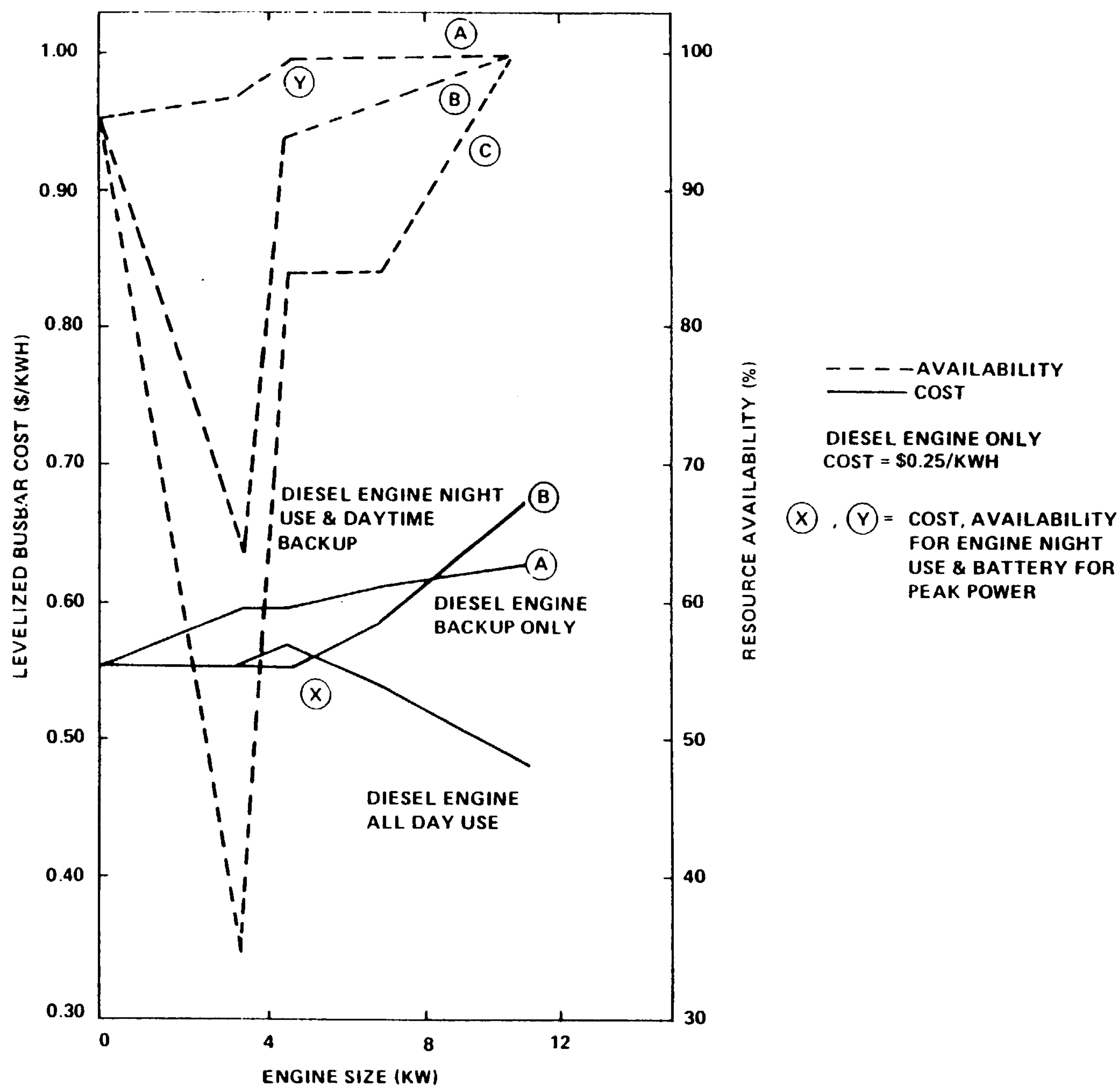


EXHIBIT 4-22: VARIATION OF COST AND AVAILABILITY FOR 100 KWH/DAY PV/DIESEL HYBRID SYSTEM

EXHIBIT 4-22: VARIATION OF COST AND AV ABILITY FOR 100 KWH/DAY PV/DIESEL HYBRID SYSTEM

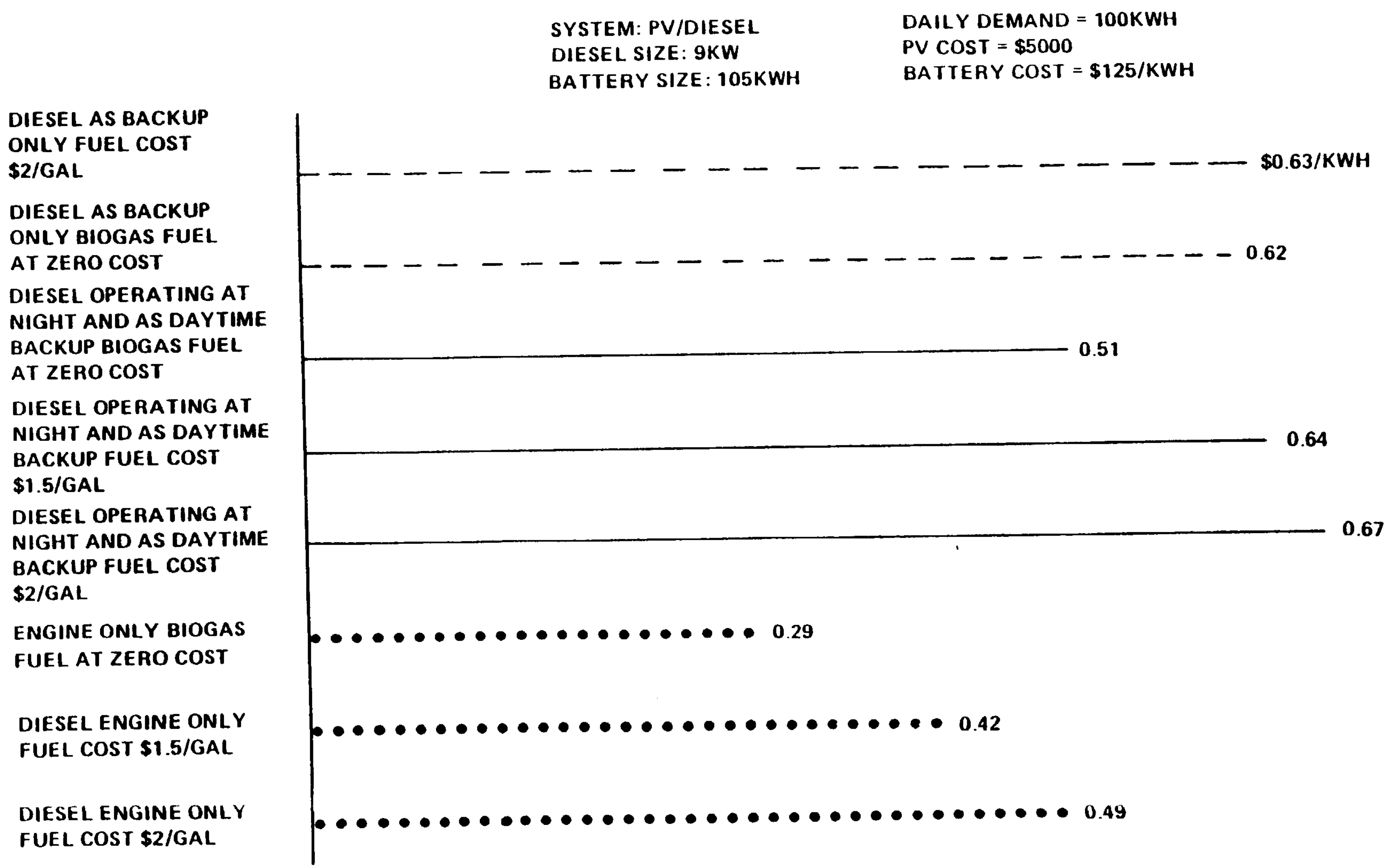


EXHIBIT 4-23: EFFECT OF FUEL COST AND OPERATING MODE ON ENERGY COSTS FOR A 100 KWH/DAY PV/DIESEL HYBRID SYSTEM

The effect on cost due to a change in debt cost was also evaluated. The results are shown in Exhibit 4-24. The graph shows the variation of cost with engine size. A lower debt cost has a significant effect on cost (cost decreases 0.43 percent for a one percent decrease in debt cost).

4.2.3 PV/Hydro Turbine System Evaluation

The following PV/hydro hybrid systems were evaluated:

- Hydro turbine only
- PV/hydro hybrid with a 10 kW hydro turbine and 1 day of battery storage.

The results shown in Exhibit 4-25 indicate that if there is a dependable water flow the least cost option, by a large margin, would be to use a hydro power system alone. Thus, different lengths of drought periods were used to evaluate PV/hydro hybrid systems. The analysis calculated the change in cost/kWh, PV array size, and battery with drought period changes. Drought period is specified as flow linearly decreasing to zero by the middle of a drought period and then linearly increasing to maximum flow by the end of the drought period. Appendix B shows a sample daily flow rate profile. All of the PV/hydro systems evaluated are more costly than both hydro and diesel stand-alone systems (Exhibit 4-26). The graph shows cost versus availability for various periods of drought.

A lower cost alternative to a PV array for extended periods of low flow is to use a diesel generator. The results of this analysis are shown in Exhibit 4-27. The graph shows levelized annual cost as a function of number of months of drought for PV and diesel generators. Even when the cost of PV is lowered from $5000/kWp to $3000/kWp, PV is still more costly than a diesel generator as backup to a hydroturbine. The results indicate that a PV/hydro hybrid system in terms of cost and availability is not a viable alternative.

4.2.4 PV/Fuel Cell System Evaluation

The following PV/fuel cell hybrid systems were evaluated:

- Fuel cell only
- PV/fuel cell with fuel cell allowed to operate all the time
- PV/fuel cell with fuel cell operating at night with 1 day of battery storage
- PV/fuel cell with fuel cell operating at night with 3 days of battery storage

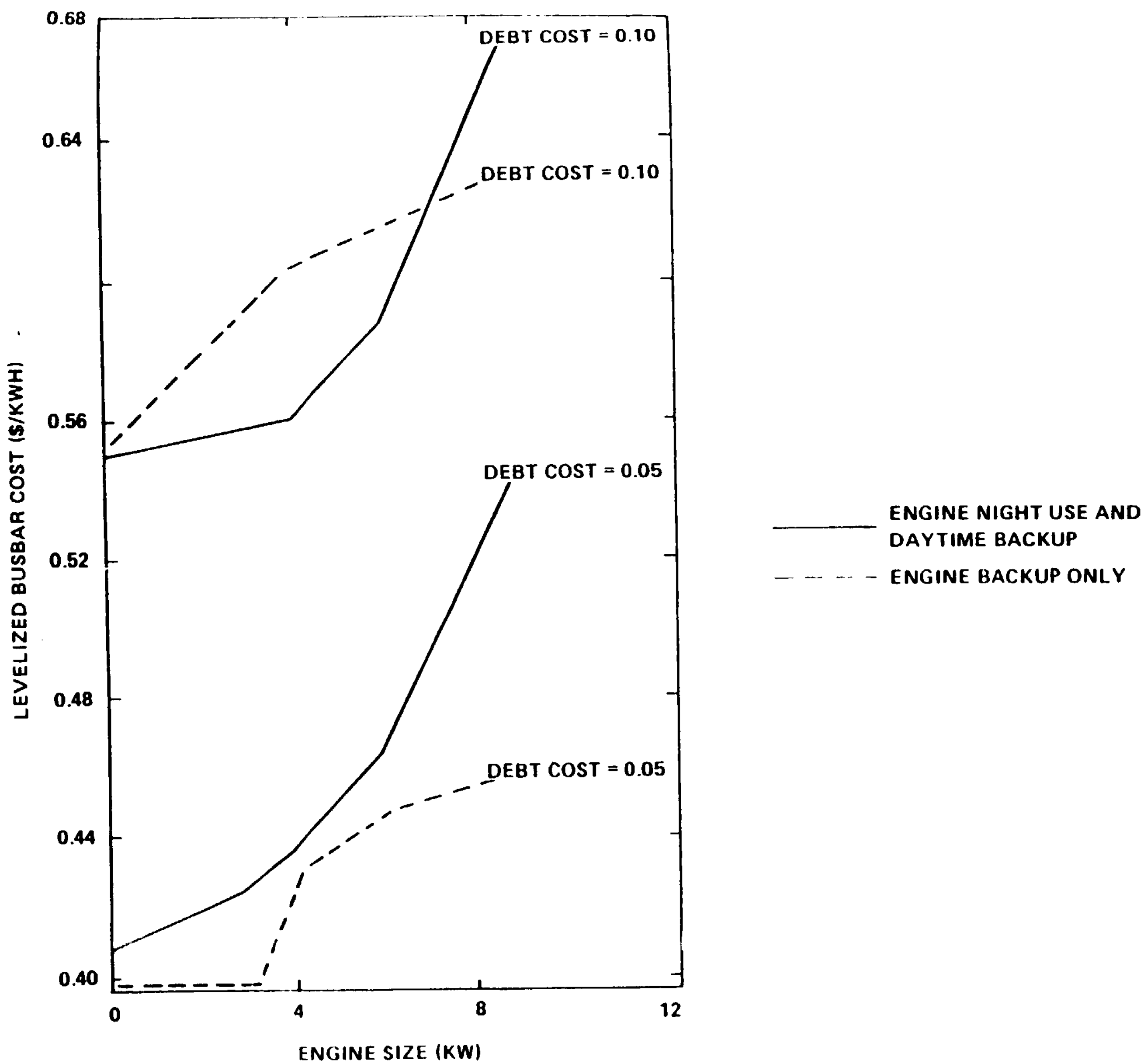


EXHIBIT 4-24: EFFECT OF DEBT COST ON ENERGY COST FOR 100 KWH/DAY PV/DIESEL HYBRID SYSTEM

EXHIBIT 4-25

100 kWh/DAY PV/HYDRO HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (lb)	PV ARRAY SIZE* (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	176.2	0	0	0.88	32.5	115700
	0	0	176.2	1	101.5	0.56	96.2	133400
	0	0	176.2	3	304.5	0.72	98.2	162800
	0	0	176.2	5	507.5	0.86	98.8	190200
HYDRO TURBINE ONLY	10.0	0	0	0	0	0.19	100.0	53000
PV/HYDRO WITH DROUGHT FROM JUNE 1 TO AUG. 1	10.0	0	145.4	1	81.9	0.70	98.9	165500
PV/HYDRO WITH DROUGHT FROM JUNE 1 TO SEP. 1	10.0	0	147.2	1	86.0	0.71	97.9	167100
PV/HYDRO WITH FLOW PEAKING DURING WINTER LOW DURING SUMMER	10.0	0	90.9	1	82.3	0.56	98.5	132800
PV/HYDRO DROUGHT FROM JUNE 1 TO SEP. 1, 10 DAY SIZING PERIOD	10.0	0	167.4	1	82.7	0.75	99.3	178800
DIESEL OR GASOLINE REFERENCE GENERATOR	9.0	5070	0	0	0	0.49	100.0	21000

* peak output 100 W/m^2

Input data in appendix B.

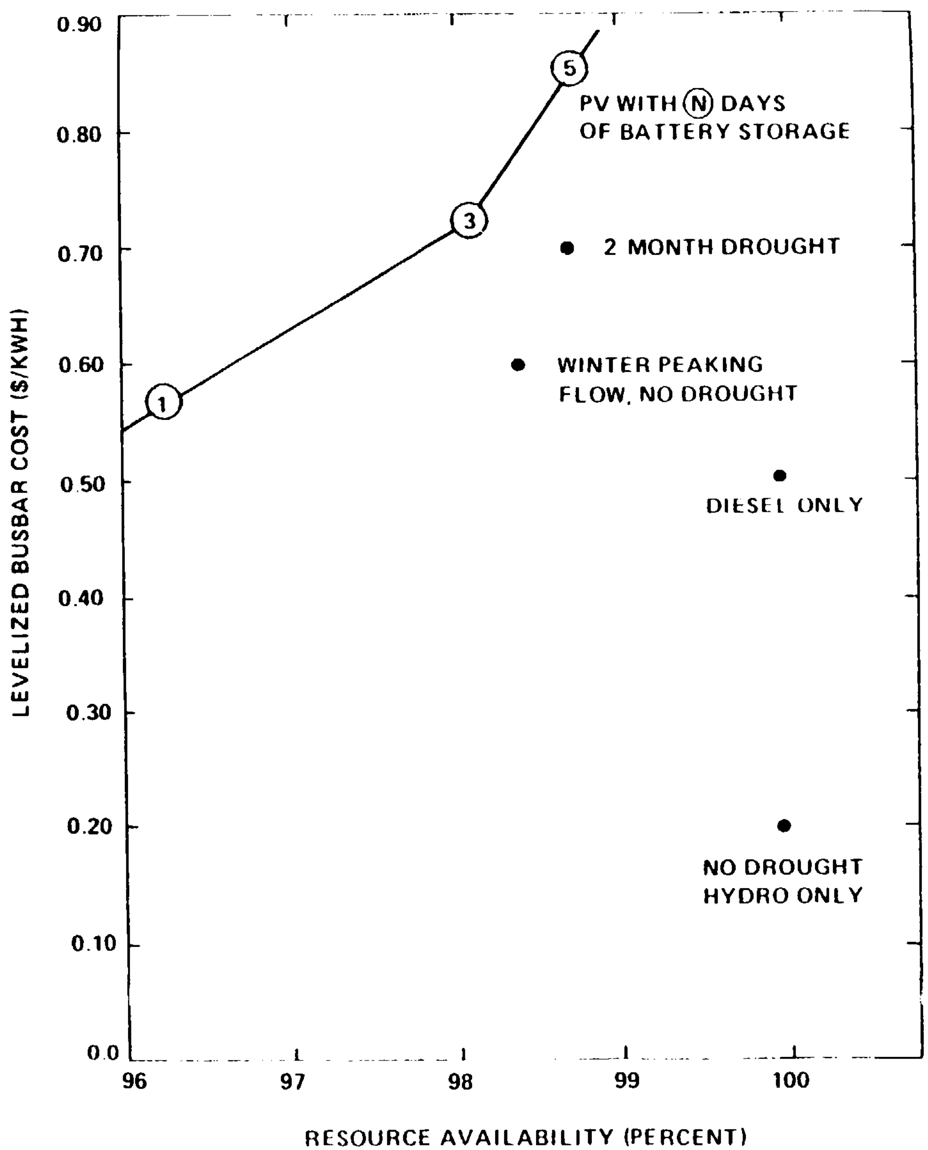


EXHIBIT 4-26: VARIATION OF ENERGY COST WITH AVAILABILITY FOR 100 KWH/DAY PV/HYDRO SYSTEM

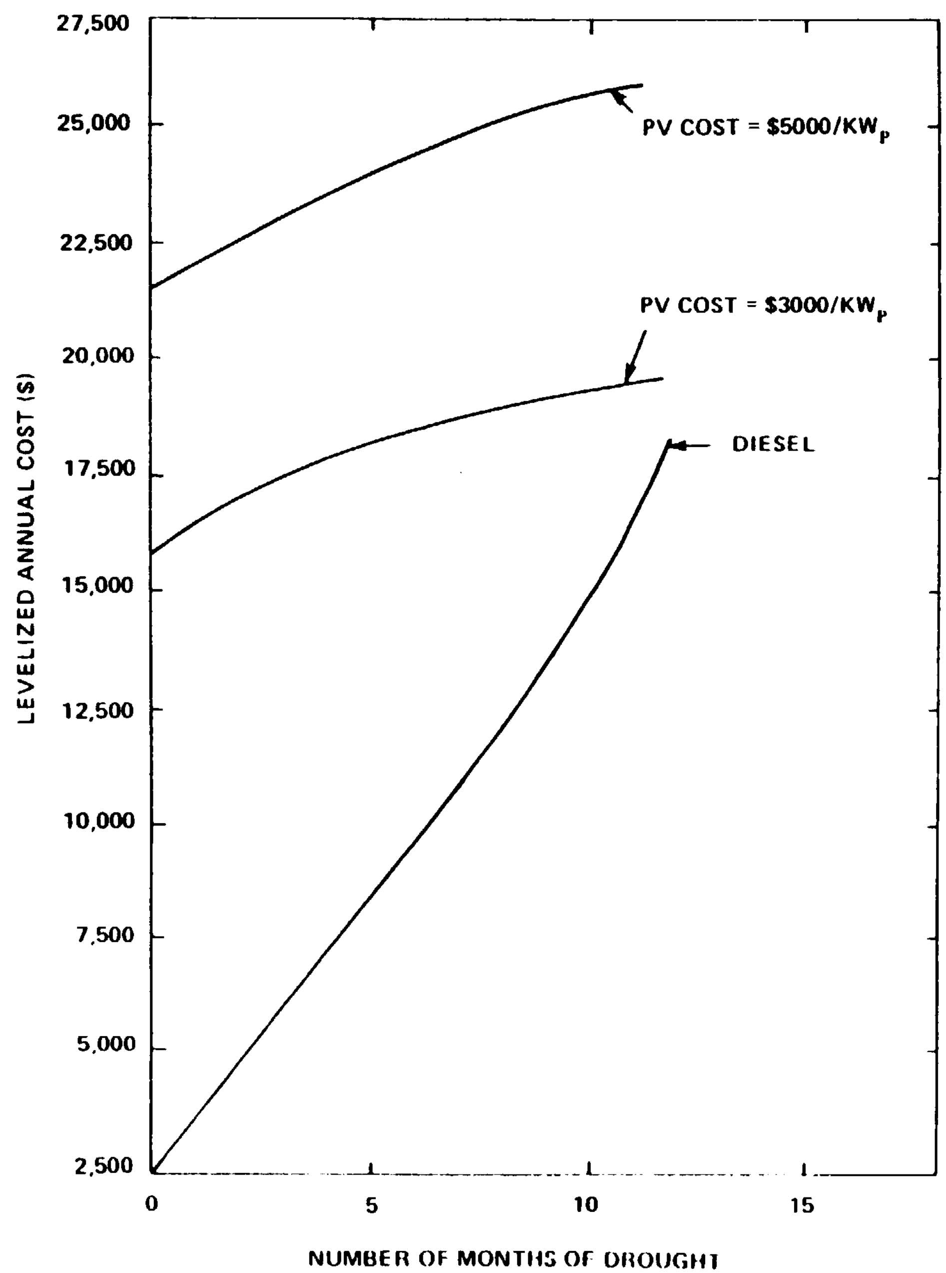


EXHIBIT 4-27: BREAKEVEN ANALYSIS OF PV AND DIESEL AS HYDRO BACKUP FOR A PV/HYDRO HYBRID SYSTEM

- PV/fuel cell with fuel cell operating at night with 5 days of battery storage

- PV/fuel cell with fuel cell operating at night with 1 day battery storage for peaking power

- PV/fuel cell with fuel cell operating at night and as day time backup with 1 day of battery storage

- PV/fuel cell with fuel cell operating at night and as day time backup with 1 day of battery storage plus with fuel cell allowed to operate below minimum recommended capacity.

The results are shown in Exhibit 4-28. The least cost option is to use the fuel cell at night with the battery used for peaking power. This option has a lower cost than a diesel-alone system. A graphical representation of these results is shown in Exhibit 4-29. The graph shows cost and availability versus fuel cell size. Points X and Y on the exhibit represent cost and availability of a PV/fuel cell hybrid, with the fuel cell operating at night and with the battery used for peaking power. To get the same availability, a larger fuel cell operating full-time would be needed and its cost would be much higher, as shown by line B in Exhibit 4-29. Thus, the optimal configuration for a PV/fuel cell hybrid is to use the fuel cell at night and use the battery for peaking power.

4.3 PV Hybrid Systems for 1000 kWh/day Demand

Under this demand range three PV hybrid systems were evaluated (1) PV/wind, (2) PV/diesel, and (3) PV/hydro. A summary of the results obtained is shown in Exhibit 4-30. The underlined numbers indicate the best option for each hybrid system in terms of cost and availability. A stand-alone diesel engine generator is used as reference for cost and availability comparison.

4.3.1 PV/Wind System Evaluation

The following PV/wind hybrid systems were evaluated:

- PV/wind with no battery storage

- PV/wind with 1 day of battery storage

- PV/wind with 3 days of battery storage

- PV/wind with 5 days of battery storage

The results obtained for this hybrid system are shown in Exhibit 4-31. The lowest cost/high availability hybrid option is to use a PV/wind system with one day of battery storage. This PV hybrid is more costly than a diesel-alone power system. However, given the

EXHIBIT 4-28

100 kWh/DAY PV/FUEL CELL HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (lb)	PV ARRAY SIZE * (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	176.2	0	0	0.88	32.5	115700
	0	0	176.2	1	101.5	0.56	96.2	133400
	0	0	176.2	3	304.5	0.72	98.2	162800
	0	0	176.2	5	507.5	0.86	98.6	190200
FUEL CELL ENGINE ONLY	6.0	21920	0	0	0	0.53	100.0	26400
PV/FUEL CELL WITH ENGINE OPERATING ALL THE TIME	3.0	10150	56.2	1	29.0	0.46	78.9	55860
	6.0	21920	0	1	0	0.53	100.0	26400
PV/FUEL CELL WITH ENGINE OPERATING AT NIGHT	3.0	4510	100.9	1	56.5	0.49	87.2	88320
	6.0	8936	100.8	1	56.6	0.60	87.2	93930
PV/FUEL CELL WITH ENGINE OPERATING AT NIGHT + 3 DAY BATTERY	3.0	4504	100.9	3	169.6	0.58	87.3	104600
	6.0	8926	100.8	3	169.6	0.69	87.2	110200
PV/FUEL CELL WITH ENGINE OPERATING AT NIGHT + 1 DAY BATTERY, ENGINE WITH OPERATING PRIORITY OVER BATTERY	3.0	6083	100.9	1	56.5	0.48	98.2	88320
DIESEL OR GASOLINE REFERENCE GENERATOR	9.0	5070 (gl)	0	0	0	0.49	100.0	21000

* peak output 100 W/m^2

Input data in appendix B.

EXHIBIT 4-28 (CONCLUDED)

100 kWh/DAY PV/FUEL CELL HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (lb)	PV ARRAY SIZE * (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV/FUEL CELL WITH ENGINE OPERATING AT NIGHT + 5 DAY BATTERY	3.0 6.0	4494 8906	100.9 100.8	5 5	282.6 283.0	0.67 0.78	87.3 87.2	122600 128200
PV/FUEL CELL WITH ENGINE OPERATING AT NIGHT + 5 DAY BATTERY, ONE DAY SIZING PERIOD	0 3.0 6.0	0 5 16	415.7 235.5 223.1	5 5 5	443.5 120.2 123.1	1.39 0.76 0.75	100.0 99.9 99.9	325900 183000 181700
PV/FUEL CELL WITH ENGINE OPERATING AT NIGHT AND AS DAYTIME BACKUP	6.0	8174	100.8	1	56.6	0.64	99.9	93930
PV/FUEL CELL same as above ALLOWED TO RUN BELOW CAPACITY	6.0	8502	100.8	1	56.6	0.65	100.0	93930
DIESEL OR GASOLINE REFERENCE GENERATOR	9.0	5070 (gl)	0	0	0	0.49	100.0	21000

* peak output 100 W/m^2

Input data in appendix B.

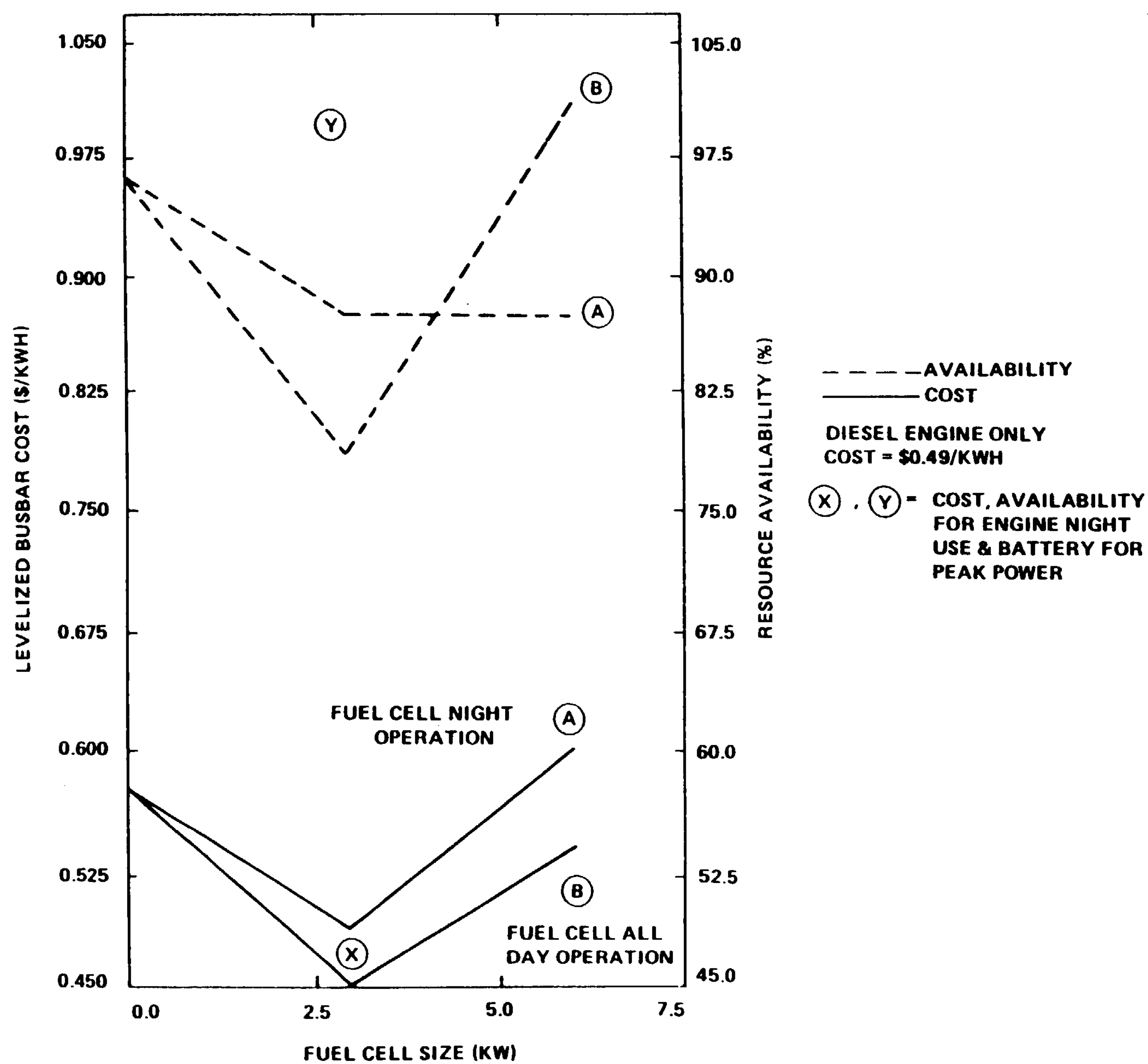


EXHIBIT 4-29: VARIATION OF COST & AVAILABILITY FOR 100 KWH/DAY PV/FUEL CELL HYBRID SYSTEM

EXHIBIT 4-30

SUMMARY RESULTS FOR 1000 kWh/DAY HYBRID SYSTEMS

HYBRID SYSTEM	LOWEST COST SYSTEM WITH RESOURCE AVAILABILITY ≥ 80%			HIGHEST AVAILABILITY SYSTEM WITH LOWEST COST		
	COST \$/KWH	AVAIL-ABILITY	PV SIZE (M^2)/ALT. SIZE (KW)	COST \$/KWH	AVAIL-ABILITY	PV SIZE (M^2)/ALT. SIZE (KW)
WIND MACHINES						
1. With 1 day storage	0.37	98	398/300	0.38	99	0/500
2. With 3 day storage	0.52	99	756/200	0.60	100	0/500
3. With 5 day storage	0.66	100	756/200	0.83	100	756/200
DIESEL ENGINE						
1. All day operation	0.33	84	210/60	0.25	100	0/60
2. Night operation & as backup	0.45	97	1008/60	0.47	100	1008/75
3. Only as backup	0.57	100	1762/75	0.57	100	1762/75
4. Night operation & battery for peaking power	0.45	98	1008/60			
HYDRO TURBINE						
1. No drought, adequate flow	0.15	100	0/100			
2. 1 month drought	0.65	99	1472/100			
3. 2 month drought	0.65	98	1472/100			
4. 3 month drought	0.66	97	1475/100			
5. Winter peaking flow	0.44	98	889/100			

EXHIBIT 4-31

1000 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	1762.0	0	0	0.88	32.5	1152000
	0	0	1762.0	1	1015.0	0.56	96.2	1296000
	0	0	1762.0	3	3045.0	0.70	98.2	1586000
	0	0	1762.0	5	5075.0	0.85	98.8	1872000
PV/WIND WITH WIND PROFILE WINTER HIGH AND SUMMER LOW, NIGHT PEAKING	50.0	0	1293.0	0	0	0.51	52.1	921000
	100.0	0	1114.0	0	0	0.46	60.9	863500
	200.0	0	756.0	0	0	0.41	60.8	748700
	300.0	0	397.8	0	0	0.41	51.3	633700
	500.0	0	0	0	0	0.40	52.8	595000
same as above + 1 DAY OF BATTERY STORAGE	50.0	0	1293.0	1	793.6	0.44	98.2	103700
	100.0	0	1114.0	1	832.2	0.46	98.7	980300
	150.0	0	935.1	1	832.2	0.40	98.5	927100
	200.0	0	756.0	1	926.8	0.39	98.3	881400
	300.0	0	397.8	1	1230.0	0.37	97.7	804400
	500.0	0	0	1	1583.0	0.38	98.7	809800
same as above + 3 DAYS OF BATTERY STORAGE	50.0	0	1293.0	3	2381.0	0.56	99.1	1270000
	100.0	0	1114.0	3	2396.0	0.54	99.3	1214000
	200.0	0	756.0	3	3780.0	0.52	99.2	1147000
	300.0	0	397.8	3	3690.0	0.54	98.8	1146000
	500.0	0	0	3	4748.0	0.60	99.6	1240000
same as above + 5 DAYS OF BATTERY STORAGE	50.0	0	1293.0	5	3968.0	0.68	99.7	1502000
	100.0	0	1114.0	5	3993.0	0.66	99.9	1448000
	200.0	0	756.0	5	4664.0	0.66	99.8	1413000
	300.0	0	397.8	5	6150.0	0.72	99.5	1487000
	500.0	0	0	5	7913.0	0.82	100.0	1669000
DIESEL OR GASOLINE REFERENCE GENERATOR	75.0	32950	0	0	0	0.25	100.0	107000

* peak output 100 W/m^2

Input data in appendix B

potential for PV and wind machine cost reductions, and fuel cost increases, this hybrid system might be worth investigating further. Exhibit 4-32 shows the variation of cost and availability with wind machine size. It can be seen that there is a definite minimum where a PV/wind hybrid is less costly than either system alone. The minimum cost point is more distinct here than in the 10 or 100 kWh/day cases, since batteries are larger and therefore have greater influence on cost. None of the hybrid systems are less costly than a diesel stand-alone system making PV/wind hybrids, in this demand range, only marginal under the existing cost assumptions. An evaluation was conducted to test the sensitivity of cost to changes in PV array costs and battery costs. It was found that in this demand range, busbar cost is more sensitive to PV array costs rather than to battery costs. The results are shown in Exhibit 4-33.

4.3.2 PV/Diesel Engine System Evaluation

Under this demand range five systems configurations were evaluated, as follows:

- Diesel engine alone
- PV/diesel with engine allowed to operate all the time.
- PV/diesel with engine operating at night and as daytime backup
- PV/diesel with engine operating as backup only
- PV/diesel with engine operating at night with battery for peaking power.

All the above hybrids used one day of battery storage. The results are shown in Exhibit 4-34. The least cost hybrid option with high availability is to use the engine at night with battery for peaking power. Exhibit 4-35 shows the variation of cost and availability with engine size. None of the hybrids have a cost lower than a diesel alone system. However, if high reliability is desired, a PV/diesel hybrid might be preferred to a diesel generator.

Points X and Y again indicate cost and availability when the battery is used for peaking power at night.

4.3.4 PV/Hydro System Evaluation

The following PV/hydro hybrid systems are evaluated:

- Hydro turbine alone
- PV/hydro hybrid with a 100kW hydroturbine and one day of battery storage.

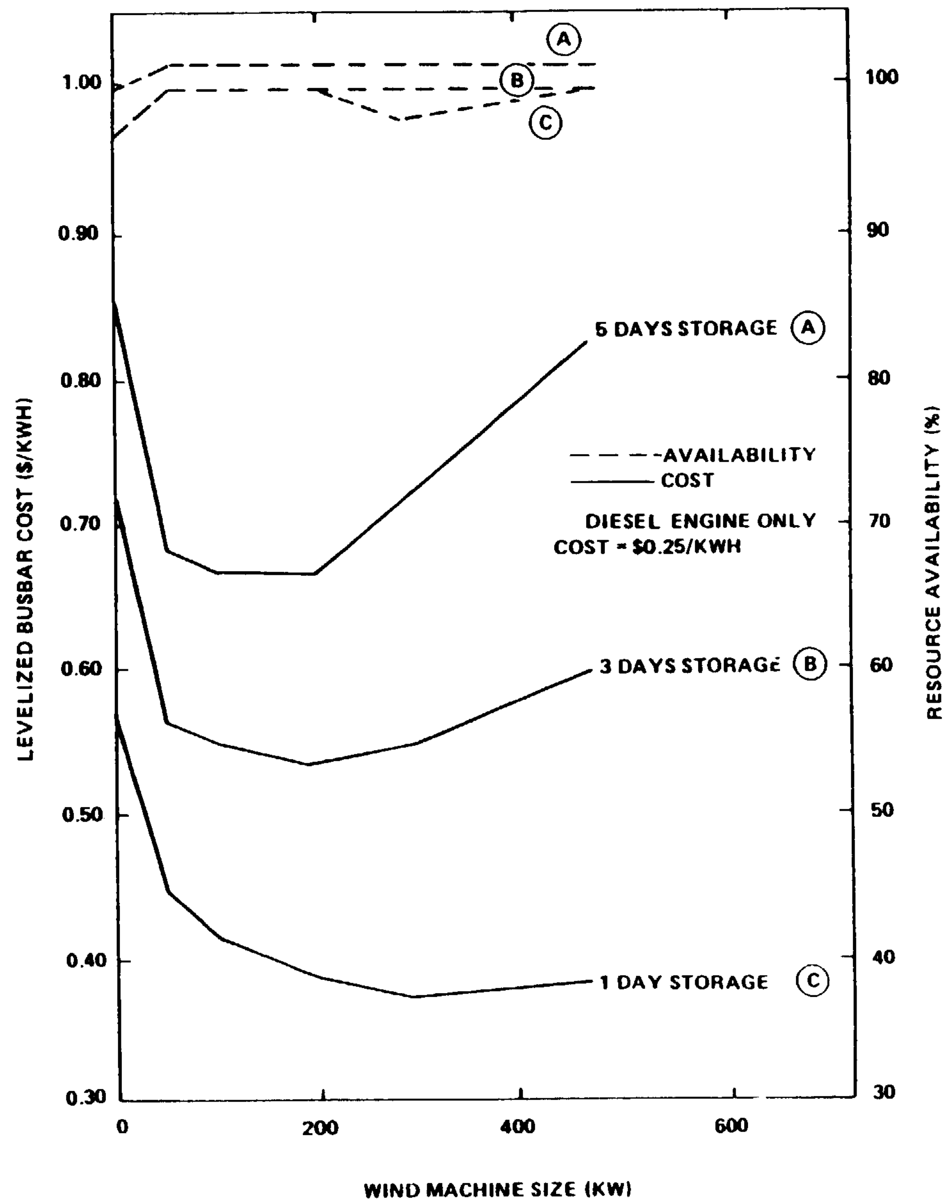


EXHIBIT 4-32: VARIATION OF COST AND AVAILABILITY FOR 1000 KWH/DAY PV/WIND HYBRID SYSTEM

EXHIBIT 4-33

SENSITIVITY OF LEVELIZED BUSBAR COSTS
TO PV AND BATTERY COSTS FOR A 1000 kWh/DAY
PV/WIND HYBRID SYSTEM (3 DAYS STORAGE)

MINIMUM COST SYSTEM		PV ARRAY COSTS $3000/kWp	PV ARRAY COSTS $5000/kWp	PERCENT CHANGE IN ENERGY COSTS FOR A ONE PERCENT DECREASE IN ARRA COSTS
BATTERY COSTS	$150/kWh	.460 $/kWh WIND = 100 kW PV = 1114 M^2 BATT = 2396 kWh	.569 $/kWh WIND = 200 kW PV = 756 M^2 BATT = 2780 kWh	0.443
BATTERY COSTS	$125/kWh	.428 $/kWh WIND = 100 kW PV = 1114 M^2 BATT = 2396 kWh	.522 $/kWh WIND = 200 kW PV = 756 M^2 BATT = 2780 kWh	0.450
PERCENT CHANGE IN ENERGY COSTS FOR A ONE PERCENT DECREASE IN BATTERY COSTS		0.374	0.354	

EXHIBIT 4-34

1000 kWh/DAY PV/DIESEL HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY SIZE* (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	1762.0	0	0	0.87	32.5	1152000
	0	0	1762.0	1	1015.0	0.56	96.2	1296000
	0	0	1762.0	3	3045.0	0.70	98.2	1584000
	0	0	1762.0	5	5075.0	0.84	98.8	1872000
DIESEL ENGINE ONLY	75.0	32950	0	0	0	0.25	100.0	107000
PV/DIESEL WITH ENGINE OPERATING ALL THE TIME	30.0	15960	752.0	1	415.6	0.43	35.4	693200
	60.0	27380	209.2	1	115.6	0.33	83.7	309600
PV/DIESEL WITH ENGINE OPERATING AT NIGHT AND AS DAYTIME BACKUP	30.0	9086	1131.0	1	625.0	0.47	63.7	892700
	60.0	12800	1008.0	1	565.7	0.45	96.5	843300
	75.0	14090	1008.0	1	566.0	0.47	100.0	857300
PV/DIESEL WITH OPERATING AS BACKUP ONLY	30.0	750	1762.0	1	1051.0	0.57	96.9	1320000
	60.0	906	1762.0	1	1015.0	0.57	99.6	1352000
	75.0	1013	1762.0	1	1015.0	0.56	100.0	1366000
PV/DIESEL WITH ENGINE OPERATING AT NIGHT, ENGINE WITH OPERATING PRIORITY OVER BATTERY	60.0	13600	1008.0	1	565.7	0.45	98.5	843300

* peak output 100 W/m^2

Input data in appendix B.

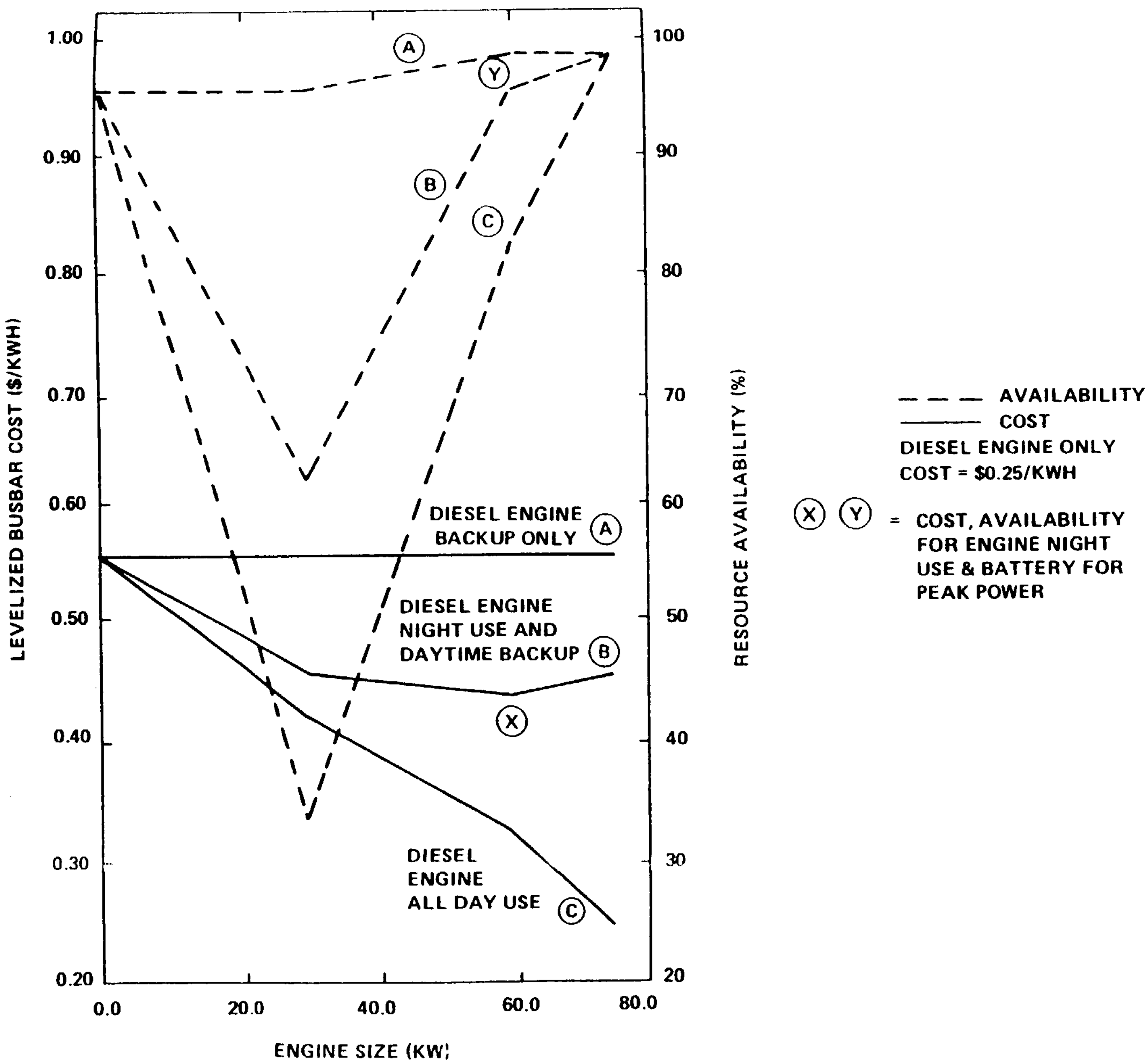


EXHIBIT A-[illegible]: VARIATION OF COST AND AVAILABILITY FOR 1000 KWH/DA

Results obtained for this hybrid system evaluation are given in Exhibit 4-36. Similar to the small PV/hydro systems, the least cost option, assuming a dependable water flow, is to use hydro power alone. This is shown in Exhibit 4-37.

Given the relatively low flow rates needed even for a 100 kW hydroturbine, it is unlikely that a hydroturbine will be installed at such a site unless the water is used for other purposes such as irrigation. In such cases, water flow is determined by irrigation schedules and not by natural stream flow. In such circumstances, a PV/hydro system might be economically feasible. However, since the application is extremely site specific, PV/hydro in general does not appear to be an attractive conceptual design candidate.

4.4 Effect of Random Insolation Variation

To test the sensitivity of array size, battery size, availability and cost to random variation in insolation, 27 years of insolation data was generated and used to size, cost, and simulate the performance of a PV/battery power system. The system used was PV with 5 days of battery storage. The results are shown in Exhibit 4-38. The graph shows array size, battery size and cost as a function of availability. The chart gives an indication that the component most affected by the insolation variation is the battery size. The array size, cost, and availability are not greatly affected. The battery is most affected since it acts as a buffer in matching energy supply and demand when there are unexpected solar insolation variations.

4.5 Institutional Factors Evaluation

The assessment of PV hybrid systems from developing country institutions viewpoint is based on an identification and analysis of relevant criteria and on field interviews conducted with developing country rural electrification officials. With reference to the field interviews, it was found that system unit energy production costs can be viewed as the predominant factor that will affect hybrid technology adoption. The interviews also indicated that suppliers' credit can be expected to be the most sensitive factor affecting system acceptance, and that on-going programs related to the country's renewable energy resource base will be an underlying factor affecting technology acceptance. Therefore, these findings suggest that developing country institutional and cultural factors (which shall be considered in this assessment) should be considered as the "secondary" base in evaluating system choice. Technology and cost factors should most appropriately be considered as the "primary" base in making the system choices.

Based on an analysis of institutional and other issues, summary questions were prepared. For analytical purposes, it was felt and

EXHIBIT 4-36

1000 kWh/DAY PV/HYDRO HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY	0	0	1762.0	0	0	0.87	32.5	1152000
	0	0	1762.0	1	1015.0	0.56	96.2	1296000
	0	0	1762.0	3	3045.0	0.70	98.2	1584000
	0	0	1762.0	5	5075.0	0.84	98.8	1872000
HYDRO TURBINE ONLY	100.0	0	0	0	0	0.15	100.0	430000
PV/HYDRO WITH DROUGHT FROM JUNE 1 TO AUGUST 1	100.0	0	1472.0	1	860.0	0.65	98.9	1533000
PV/HYDRO WITH DROUGHT FROM JUNE 1 TO SEPT. 1	100.0	0	1472.0	1	860.0	0.65	97.9	1533000
PV/HYDRO WITH DROUGHT FROM JUNE 1 TO OCT. 1	100.0	0	1475.0	1	975.2	0.66	97.1	1549000
PV/HYDRO WITH FLOW PEAKING DURING WINTER LOW DURING SUMMER	100.0	0	889.1	1	596.0	0.45	98.4	1053000
DIESEL OR GASOLINE REFERENCE GENERATOR	75.0	13600	0	0	0	0.25	100.0	107000

* peak output 100 W/m^2

Input data in appendix B.

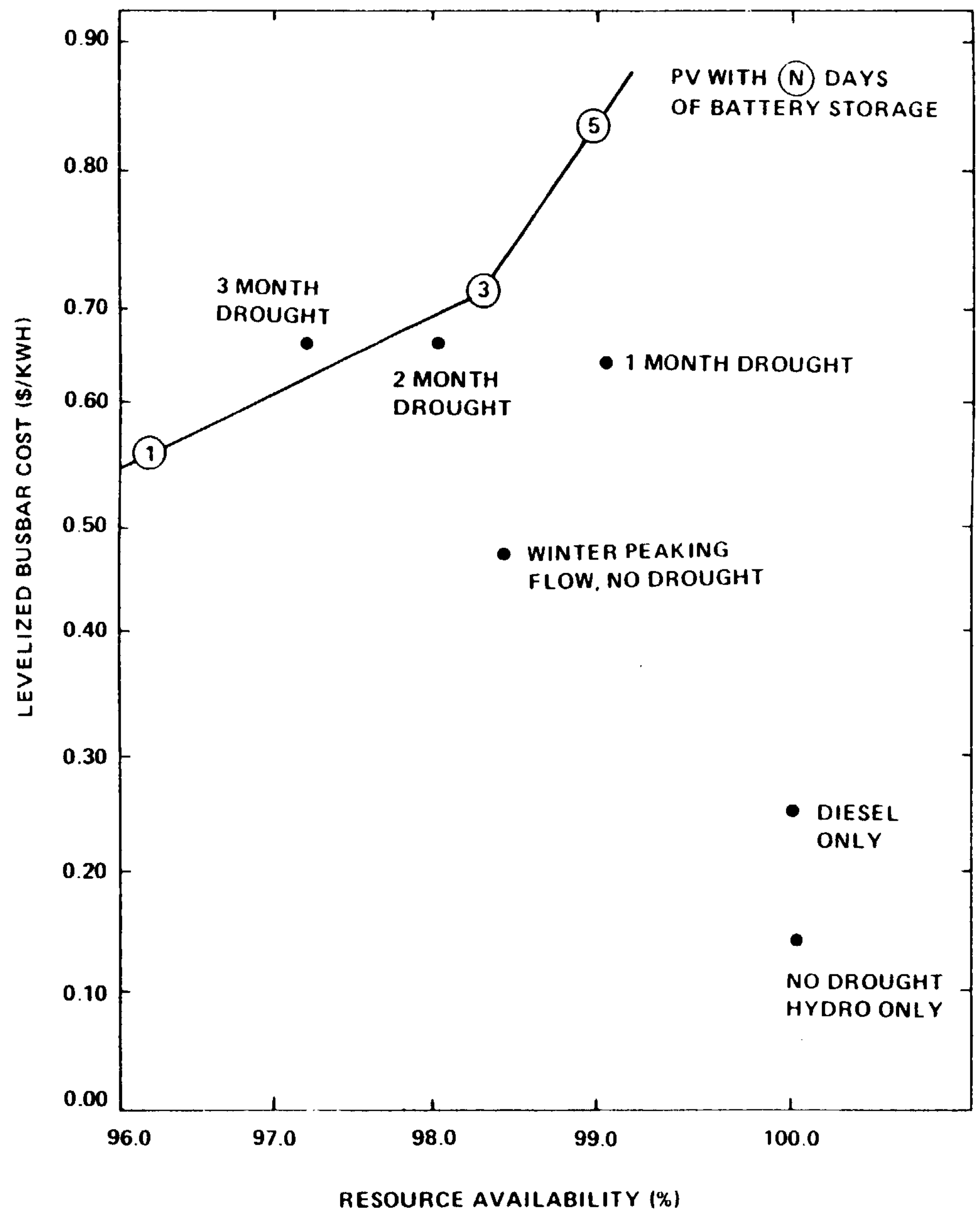
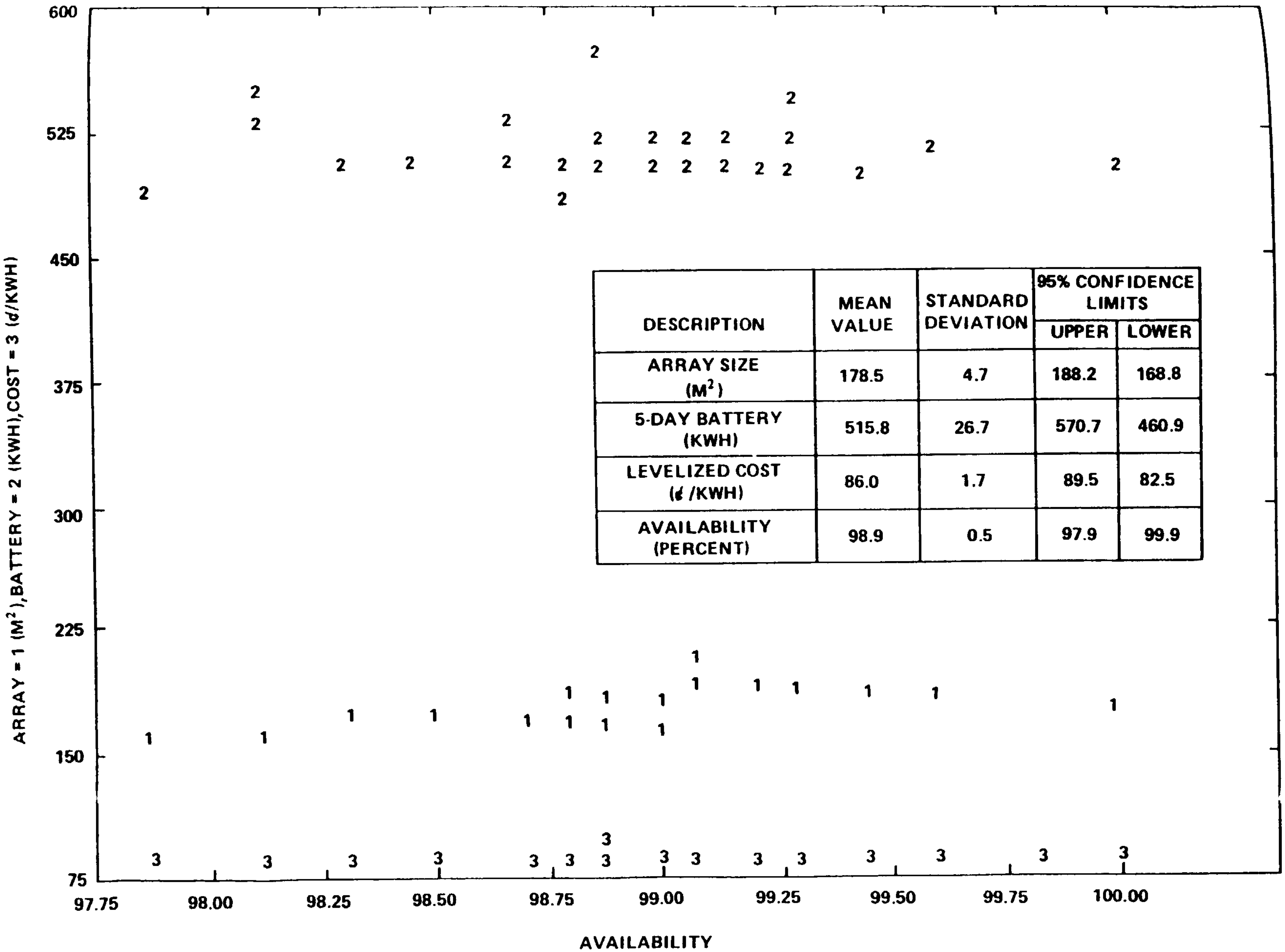


EXHIBIT 4-37: VARIATION OF COST WITH AVAILABILITY FOR A 1000 KWH/DAY PV/HYDRO HYBRID SYSTEM

... VARIATION OF COST WITH AVAILABILITY FOR A 1000 KWH/DAY PV/HYDRO HYBRID SYSTEM



DESCRIPTION	MEAN VALUE	STANDARD DEVIATION	95% CONFIDENCE LIMITS	
			UPPER	LOWER
ARRAY SIZE (M^2)	178.5	4.7	188.2	168.8
5-DAY BATTERY (KWH)	515.8	26.7	570.7	460.9
LEVELIZED COST (¢/KWH)	86.0	1.7	89.5	82.5
AVAILABILITY (PERCENT)	98.9	0.5	97.9	99.9

EXHIBIT 4.3?: EFFECT OF RANDOM INSOLATION VARIATION FOR 100 KWH/DAY

assumed that these questions did include the major factors used by developing country decisionmakers in assessing system acceptance and preference. The questions listed were:

A. From the Rural Development Decision-Makers' Viewpoint-

1. To what degree does the technology lend itself to mobility and application countrywide?

2. To what degree will technology application develop village by-product industry and employment opportunities?

3. To what degree will the technology disrupt settlement patterns and the ecology?

4. To what degree will technology application foster community "in-kind" contributions.

B. From the Electric Utility Sector Decision-Makers' Viewpoint -

1. To what degree will technology application require "in-country" field testing and "in-depth" site planning analysis?

2. To what degree will technology application require the need for agency approvals, and the need for local technical and operating skills?

C. From the Finance Sector Decision-Makers' Viewpoint -

1. How much of the system equipment and spare parts can be developed and produced locally?

2. To what degree does the technology lend itself to private sector ownership and host country commercial credit attractiveness?

The following assessment factors then were extracted from the set of questions:

- system mobility
- countrywide application
- industry by-product potential
- local employment generation potential
- least settlement disruption
- least ecological disruption
- system labor inputs
- system materials inputs
- least field testing requirements
- least site planning requirements
- least agency approval requirements
- least technical skills requirements
- local availability - equipment
- local availabiltiy - spare parts

- attractability - private sector ownership
- attractability - commercial credit

Exhibit 4-39 records how the ten system alternatives were evaluated and ranked. Each factor was assessed against each system alternative. A value of one point was assigned to the most acceptable alternative. A value of two points was assigned to the next most acceptable alternative and so forth, with ten points indicating the least acceptable alternative. Since sixteen factors were used in the evaluation, a total score of sixteen (16) points for any one alternative would indicate the most optimal measurement of acceptability. Conversely, a total score of one hundred and sixty (160) for any one alternative would indicate the least optimal measurement of acceptability.

Since the evaluation includes a disproportionate number of factors attributed to the rural development sector viewpoint, an alternative assessment approach was made. The approach consisted of assessing alternatives according to sector rank scores. Since three sector rank scores were involved, a total point score of thirty (30) would indicate the least optimal assessment possible. As indicated on Exhibit 4-39, only minimal sensitivity existed in the outcome of system ranking when this evaluation approach was used.

The final ranking of system alternatives is found in Exhibit 4-40. This ranking combines the results from the two assessment approaches.

4.6 Hybrid Systems Recommendations

The results from all the evaluations, including institutional factors, give an indication as to which systems would most likely be accepted and be economically feasible. Exhibit 4-41 shows the ranked order of the systems recommended as the best candidates for further detailed conceptual design. PV/diesel for 100 kWh/day is ranked first because it is competitive with conventional power systems, it is the most widely accepted technology, and it has the largest applicability worldwide. Ranked second only because of reduced applicability and technology acceptability is PV/wind for 100 kWh/day. Its busbar cost is less than the first system but as it depends on two environmental sources, its world applicability is less. Ranked third is PV/fuel cell for 100 kWh/day. It has lower cost than the first system but higher than the second. It has been ranked lower mainly because it is a new, commercially unproven technology.

The fourth system, PV/wind for 10 kWh/day, has lower cost than a stand-alone gasoline engine but has higher costs than a "PV only" system. It has been recommended because the hybrid can achieve a higher availability than a "PV only" system at a lower cost. The fifth ranked system, PV/wind for 1000 kWh/day, was selected even though its costs were higher than a "diesel only" system, since in

EXHIBIT 4-39

OVERALL RANKING OF SYSTEMS

Assessment Factors	Wind Energy Conversion Systems 10 kW	Wind Energy Conversion Systems 100 kW	Hydroelectric Generators 10 kW	Hydroelectric Generators 100 kW	Diesel/Gasoline Generators 3 kW	Diesel/Gasoline Generators 10 kW	Diesel/Gasoline Generators 100 kW	Closed Cycle Vapor Turbo Generators 5 kW (Max.)	Fuel Cell 5 kW	Fuel Cell 40 kW
A. 1.	7	8	9	10	1	2	4	3	5	6
2.	7	8	9	10	1	2	3	6	4	5
3.	4	3	2	1	9	8	7	10	6	5
4.	6	3	5	1	9	7	4	10	8	2
5.	8	9	7	10	2	4	6	1	3	5
6.	7	8	6	9	3	5	10	1	2	4
7.	4	3	2	1	9	8	7	10	6	5
8.	5	6	2	3	7	8	9	10	4	1
Sub-totals	(7.5) 1/ 48 2/	(7.5) 48	(4) 42	(6) 45	(3) 41	(5) 44	(9) 50	(10) 51	(2) 38	(1) 33
B. 1.	6	7	5	8	1	2	3	4	9	10
2.	7	9	8	10	1	2	3	6	4	5
3.	1	7	9	10	2	4	8	5	3	6
4.	7	8	5	6	1	2	3	4	9	10
Sub-totals	(5) 21	(8.5) 31	(7) 27	(10) 34	(1) 5	(2) 10	(3) 17	(4) 19	(6) 25	(8.5) 31
C. 1.	2	7	1	3	4	5	6	8	9	10
2.	5	7	4	6	1	2	3	8	9	10
3.	3	7	4	8	1	2	6	10	5	9
4.	8	9	4	5	1	2	3	10	6	7
Sub-totals	(4.5) 18	(8) 30	(3) 13	(6) 22	(1) 7	(2) 11	(4.5) 18	(9.5) 36	(7) 29	(9.5) 36
Totals	(17) 87	(24) 109	(14) 82	(22) 101	(5) 53	(9) 65	(15.5) 85	(23.5) 106	(15) 92	(19) 100
Rankings	(6) 3/ 5 4/	(10) 10	(3) 3	(8) 8	(1) 1	(2) 2	(5) 4	(9) 9	(4) 6	(7) 7
Composite Ranking	6	10	3	8	1	2	4	9	5	7

1. Single Sector Ranking
2. Single Sector Point Score
3. Ranking by Sector Ranking
4. Ranking by Point Score

A. Rural Area Development Sector Assessment Factors
B. Electric Utility Sector Assessment Factors
C. Finance Sector Assessment Factors

2. Single Sector Point Score
3. Ranking by Sector Ranking
4. Ranking by Point Score

A. Rural Area Development Sector Assessment Factors
B. Electric Utility Sector Assessment Factors
Finance Sector Assessment Factors

EXHIBIT 4-40

RANKING OF HYBRID SYSTEMS BY INSTITUTIONAL FACTORS

RANKING	SMALL 10 kWh/day	MEDIUM 100 kWh/day	LARGE 1000 kWh/day
1.	Diesel/gasoline	Diesel/gasoline	Diesel/gasoline
2.	Fuel cells	Hydroelectric	Hydroelectric
3.	CCVT	Wind Machines	Wind Machines
4.	-	Fuel Cells	-

some applications fuel supply uncertainties or costs may preclude the use of a diesel. The PV/CCVT system has been recommended since it is most suitable for unattended operation in remote locations where very high reliability is required. Finally, a PV/diesel for 1000 kWh/day was selected because it will have greater reliability and lower fuel consumption than diesel alone.

Based on the previous analysis the first four systems shown in Exhibit 4-41 were selected for detailed conceptual design.

EXHIBIT 4-41

HYBRID SYSTEMS RECOMMENDED FOR DETAILED CONCEPTUAL DESIGN

* 1. PV/DIESEL FOR 100 KWH/DAY DEMAND, AC POWER

* 2. PV/WIND FOR 100 KWH/DAY DEMAND, AC POWER

* 3. PV/FUEL CELL FOR 100 KWH/DAY DEMAND, AC POWER, BATTERY FOR PEAKING

* 4. PV/WIND FOR 10 KWH/DAY DEMAND, DC POWER

5. PV/WIND FOR 1000 KWH/DAY DEMAND, AC POWER

6. PV/CCVT FOR 10 KWH/DAY DEMAND, DC POWER, BATTERY FOR PEAKING

7. PV/DIESEL FOR 1000 KWH/DAY DEMAND, AC POWER

* SELECTED FOR DETAILED CONCEPTUAL DESIGN

5.0 HYBRID SYSTEM CONFIGURATIONS FOR CONCEPTUAL DESIGN

Conceptual designs for PV/wind, PV/diesel and PV/fuel cell hybrids were developed for supplying AC power to a remote village in Tunisia. For the smaller system, a conceptual design for a PV/wind hybrid was developed for supplying DC village power to Utirik Island in the Marshall Islands. For each system evaluation the following costs were specified seperately:

- Capital cost for each of the following:
  - PV array ($/kW$_p$)
  - Balance of systems related to PV array ($/kW$_p$)
  - Alternate generator ($)
  - Balance of systems related to alternate generator ($/rated alternate generator capacity)
  - Battery ($/kWh of storage)
  - Balance of system for combined system ($)
- Fuel usage, if any, associated with each of the above hybrid system components
- Operation and maintenance costs associated with each of the above hybrid system components. (Specified as percent of capital costs for PV, wind, and hydropower generators and as $/hour of operation for diesel and gasoline generators and fuel cells).

5.1 PV Hybrid System Assessment for a Tunisian Village

The purpose of this section is to present the results obtained from the evaluation of several PV/wind, PV/ diesel, and PV/fuel cell hybrid systems and select systems for conceptual design.

5.1.1 Village Energy Requirements

The remote Tunisian village is assumed to require approximately 50 kWh/day of electrical energy at 220V AC with 99 percent, or better, availability. The electrical loads for the village, daily load distribution and seasonal variation used for the analysis are shown in Exhibit 5-1. The peak load is 4.67 kW.

5.1.2 Village Resource Availability

Insolation at the village is shown in Exhibit 5-2. Corresponding wind speed data is shown in Exhibit 5-3.

EXHIBIT 5-1

ELECTRICAL LOADS FOR A REMOTE VILLAGE IN TUNISIA

Application	Daily Total (kWh) Winter	Spring & Fall	Summer
Commercial			
11 Lights	1.2	0.74	0.6
2 Refrigerators	2.02	3.5	5.0
Domestic			
91 lights	15.0	10.9	5.0
13 Refrigerators	12.0	21.0	30.0
18 TV's	2.0	2.0	2.0
Public			
57 Lights	12.0	10.8	2.3
3 Refrigerators	4.0	6.7	4.7
1 Medical Refrigerator	0.75	0.75	0.75
3 TV's	0.24	0.24	0.1
1 Water pump	1.2	1.5	1.1
Total	50.41	58.13	51.55

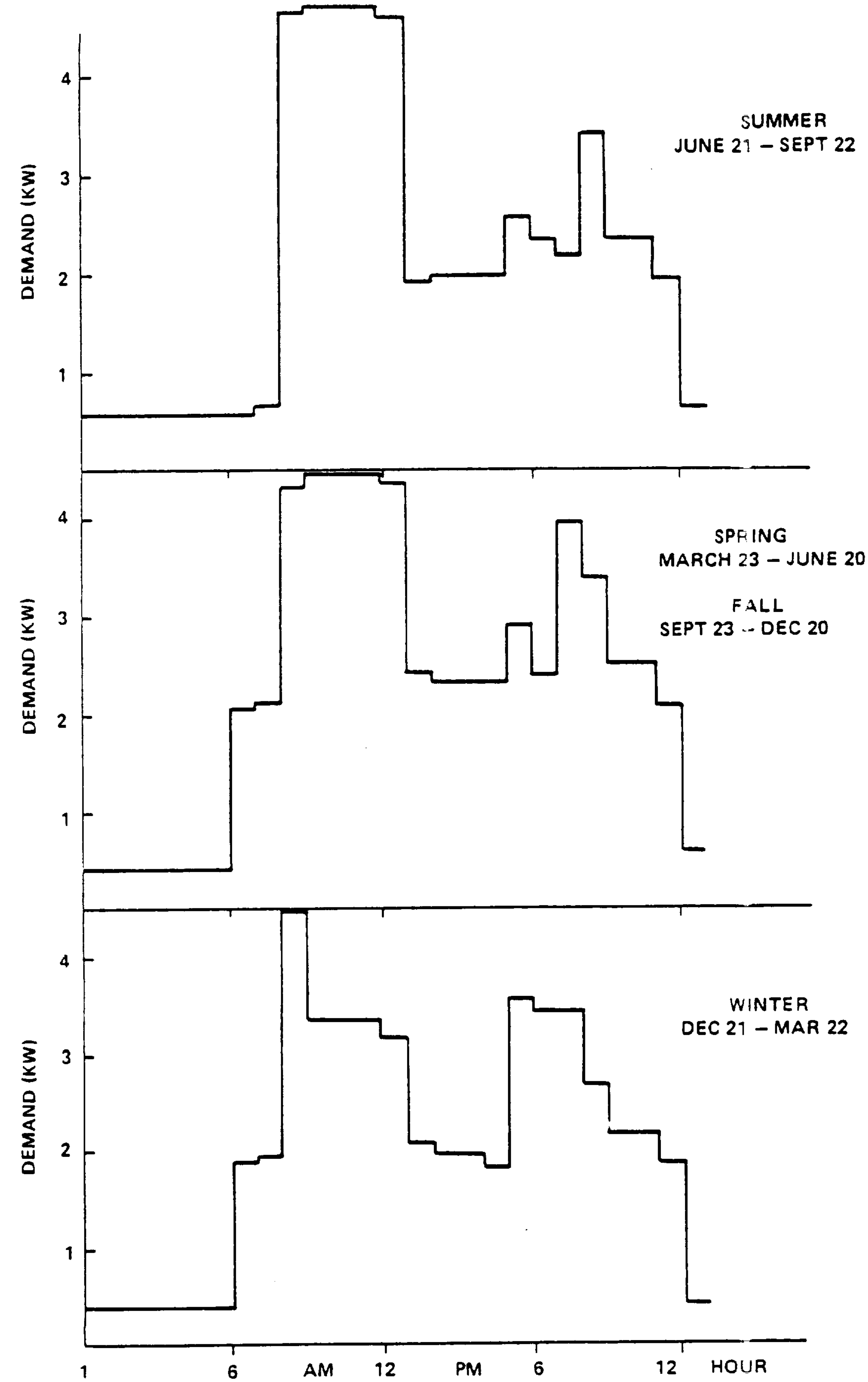


EXHIBIT 5-1: SEASONAL DAILY LOAD DISTRIBUTION FOR A REMOTE VILLAGE IN TUNISIA

5.1.3 PV Hybrid Systems Evaluated

For the village in Tunisia the hybrid systems analyzed were PV/wind, PV/diesel and PV/fuel cell supplying AC power. The input data for the different system components are shown in Exhibit 5-4.

5.1.4 PV/Wind Hybrid System Evaluation

Several PV/wind system configurations were analyzed to find the least cost system with availability of at least 99 percent. A summary of the results is shown in Exhibit 5-5. The analysis showed that at least three days of battery storage were needed to ensure an availability greater than 99 percent. The analysis also examined a number of cost and performance alternatives. They were:

- Effect of reducing PV array cost from \$5/Wp to \$2/Wp
- Effect of including a spare wind turbine and generator

The sensitivity analysis showed that reducing PV array costs from \$5/Wp to \$2/Wp reduces levelized costs by \$0.13/kWh (19%). The inclusion of a spare wind turbine and generator increases costs by about \$0.10/kWh (15%). Assuming 100% equipment availability, the results indicate that the best PV/wind system with low initial cost, low energy cost, high availability, and low battery storage consists of a 10 kW wind generator with a 59.36 m2 PV array and 202.7 kWh of battery storage. On a yearly basis, the PV array provides 12,322 kWh and the wind generator 15,951 kWh.

5.1.5 PV/Diesel Hybrid System Evaluation

Several PV/diesel system configurations were tested to find the least cost system with availability of at least 99 percent. A summary of the results is shown in Exhibit 5-6. The analysis showed that at least one day equivalent of battery storage was needed to ensure that availability was greater than 99 percent. The analysis also tested a number of cost and performance alternatives. The alternatives tested were:

- Effect of reducing PV array cost from \$5/Wp to \$2/Wp
- Effect of reversing operating protocols during night time operation of engine from a battery priority mode to a diesel generator priority mode.
- Effect of reducing fuel cost from \$3/gallon to \$2/gallon.

The sensitivity analysis showed that reducing PV cost from \$5/Wp to \$2/Wp reduced levelized costs by \$0.29/kWh (37%). The effect of reversing the operating protocols from battery with operating

EXHIBIT 5-2

SOLAR INSOLATION DATA FOR A REMOTE VILLAGE IN TUNISIA

- Location - Tunisia
- Latitude - 36.83°N
- Ground reflectance - 0.2
- Array tilt angle - 36.83°
- Clearness indices

J	F	M	A	M	J	J	A	S	O	N	D
.606	.589	.562	.628	.679	.653	.704	.696	.610	.542	.559	.543

Source: NASA/LeRC, Photovoltaic Stand-alone Systems: Preliminary Engineering Design Handbook, NASA CR-165352.

EXHIBIT 5-3

WIND SPEED DATA FOR A REMOTE VILLAGE IN TUNISIA

- Measurement Height - 10m
- Monthly mean wind speed (m/s)

J	F	M	A	M	J	J	A	S	O	N	D
6.36	6.73	6.36	6.0	5.24	5.28	4.92	4.56	4.92	5.28	5.64	6.0

- Hourly mean wind speed (m/s)

Hour:	0300	0900	1500	2100
Speed: (m/s)	5.1	6.0	6.6	5.4

Source: Calculated from average monthly wind speed values provided by NASA/LeRC.

EXHIBIT 5-4

PV HYBRID SYSTEM COMPONENT INPUT DATA

- PV array input data

Efficiency, (percent)	- 10
Cost, ($/Wp)	- 5 and 2
O&M, (percent of total PV installation cost)	- 1
PV Balance of System cost, ($/Wp)	- 2 and 1
Life, (years)	- 20

- Battery input data

Efficiency, (percent)	- 85
Maximum charging rate	- 25
Maximum discharge rate	- 25
Maximum depth of discharge	- 70
Cost, ($/kWh)	-150
Battery balance of system cost, ($/kWh)	- 17
Life, (years)	- 10

- Inverter input data

Efficiency, (percent)	- 85
Cost, ($)	- 6,000
Life, (years)	- 20

- Wind generator input data

Size (kW)	Cut-in speed (m/s)	Rated speed (m/s)	Cut-out speed (m/s)	Cost* ($)	O&M (percent of total cost)	Hub height (m)	Life (years)
1.2	4.0	11.0	13.4	9000	2.5	20	20
3.5	4.5	11.2	13.0	19000	2.5	20	20
10.0	3.1	12.1	15.7	35500	2.5	20	20
15.0	3.1	12.1	15.7	38000	2.5	20	20
25.0	4.2	11.0	25.0	49000	2.5	20	20

* Includes Tower + 20% installation

All wind generators shown were de-rated 15% from their rated KW output to account for yawing and acceleration losses.

EXHIBIT 5-4 (concluded)

PV HYBRID SYSTEM COMPONENT INPUT DATA

- **Diesel generator input data*** (diesel fuel cost $3/gal)

Size (kw)	Cost ($)	O&M ($/yr)	Life (yrs)	Minimum capacity (%)	Maximum capacity (%)	Nominal capacity (%)	Fuel consumption at different capacity levels (Gal/Hr) Idle	25%	50%	75%	100%
3.0	4000	0.26	20	50	80	60	0.16	0.21	0.26	0.3	0.34
4.0	4500	0.28	20	50	80	60	0.20	0.26	0.32	0.35	0.44
6.0	5525	0.32	20	50	80	60	0.27	0.35	0.43	0.53	0.64
9.0	6350	0.35	20	50	80	60	0.33	0.49	0.58	0.71	0.85

*Backup engine is used always.

- **Fuel Cell input data** (methanol fuel cost $1/gal)

Size (kW)	Cost ($)	O&M ($/yr)	Life (yrs)	Minimum capacity (%)	Maximum capacity (%)	Nominal capacity (%)	Methanol consumption at different capacity levels (gal/hr)* idle	25%	50%	75%	100%
3.0	7250	0.01	5	25	100	100	0.15	.435	.435	.435	.45
6.0	15500	0.04	5	25	100	100	0.3	.87	.87	.87	.9

* Methanol fuel consumption above assumes engine operates only a night.

- **Fuel consumption for daytime backup or full time operation.**

Size (kW)	Methanol consumption at different capacity levels (gal/hr) idle	25%	50%	75%	100%	constant idle (gal/yr)
3	0	0.285	0.285	0.285	0.3	1314
6	0	0.57	0.57	0.57	0.6	2628

o **Miscellaneous data**

- Fuel cost escalation (%) - 0
- Project life (yrs) - 20
- Debt cost % - 5
- Debt ratio % - 1
- PV Sizing period (days) - 30

A constant dollar analysis in 1983 dollars was used for cost comparison.

EXHIBIT 5-5

TUNISIAN VILLAGE
50 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY								
PV $5/Wp	0	0	172.9	5	559.4	1.27	99.6	214760
PV $2/Wp	0	0	172.9	5	559.4	0.84	99.6	145600
PV/WIND	1.2	0	155.2	3	302.4	1.01	98.3	172200
	3.5	0	127.1	3	247.7	0.90	98.7	154320
	10.0	0	59.4	3	202.7	0.67	99.6	116690
	15.0	0	26.0	3	218.8	0.57	99.5	98220
	25.0	0	0.0	3	247.9	0.56	100.0	95390
same as	1.2	0	155.2	3	302.4	1.04	98.3	177320
above + 1	3.5	0	127.1	3	247.7	0.95	98.7	162900
SPARE	10.0	0	59.4	3	202.7	0.76	99.6	131950
WIND	15.0	0	26.0	3	218.8	0.66	99.5	113730
GENERATOR	25.0	0	0.0	3	247.9	0.82	100.0	139680
same as	1.2	0	155.2	3	302.4	0.69	98.3	115240
above +	3.5	0	127.1	3	247.7	0.66	98.7	112060
PV COST	10.0	0	59.4	3	202.7	0.62	99.6	108190
AT $2/Wp	15.0	0	26.0	3	218.8	0.60	99.5	103380
	25.0	0	0.0	3	247.9	0.83	100.0	139680
same as	1.2	0	155.2	3	302.4	0.66	98.3	110120
above +	3.5	0	127.1	3	247.7	0.61	98.7	103480
NO SPARE	10.0	0	59.4	3	202.7	0.54	99.6	92930
GENERATOR	15.0	0	26.0	3	218.8	0.51	99.5	87870
	25.0	0	0.0	3	247.9	0.56	100.0	95390
DIESEL OR GASOLINE REFERENCE GENERATOR	6	3465	0	0	0	0.86	100.0	16250

* peak output 100 W/m^2

EXHIBIT 5-6

TUNISIAN VILLAGE
50 kWh/DAY PV/DIESEL HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY SIZE * (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY								
PV $5/Wp	0	0	172.9	5	559.4	1.27	99.6	214760
PV $2/Wp	0	0	172.9	5	559.4	0.84	99.6	145600
PV/DIESEL ONLY FUEL								
$3/gl	6.0	3465.0	0	0	0	0.86	100.0	16250
$2/gl	6.0	3465.0	0	0	0	0.68	100.0	16250
PV/DIESEL WITH ENGINE OPERATING AT NIGHT & AS DAYTIME BACKUP	4.0	314.6	110.0	1	66.6	0.58	84.8	104000
	4.0	314.6	110.0	5	333.0	0.84	89.1	146300
same as above WITH ENGINE PRIORITY OVER BATTERY	0	0	173.0	1	112.0	0.84	94.8	143100
	3.0	1010.0	119.0	1	70.2	0.81	98.7	109830
	4.0	1096.0	110.0	1	66.6	0.79	99.4	104000
	6.0	498.0	142.6	1	83.9	0.84	97.4	131455
	9.0	109.0	161.3	1	96.1	0.89	94.9	148025
same as above + PV COST AT $2/Wp	4.0	1096.0	110.0	1	66.6	0.50	99.4	59980

* peak output 100 W/m^2

priority over the engine to engine with operating priority over the battery at night caused a reduction in cost of $0.05/kWh (6%) and increased availability from 89.1 to 99.4 percent. Previous PV/diesel evaluations had indicated that all other possible PV/diesel hybrid configurations would increase cost with no added improvement in performance and availability, therefore the remaining alternatives were not evaluated.

Assuming 100% equipment availability, the results indicate that the best PV/diesel system with low initial cost, low energy cost, high availability, and low battery storage consists of a 4 kW diesel generator (operating at night with operating priority over the battery, and as daytime backup), a 110m2 PV array and 66.6 kWh of battery storage. On a yearly basis the PV array provides 22,830 kWh and the diesel generator provides 8,667 kWh.

5.1.6 PV/Fuel Cell Hybrid System Evaluation

Several PV/fuel cell system configurations were tested to find the least cost system with availability of at least 99 percent. A summary of the results is shown in Exhibit 5-7. The analysis showed that at least three days equivalent of battery storage was needed to ensure that availability was greater than 99 percent. The analysis also tested a number of cost and performance alternatives. The alternatives tested were:

- Effect of reducing PV array cost from $5/Wp to $2/Wp
- Effect of using the fuel cell for different periods of time ranging from operating it all the time, to night time plus daytime backup operation, and using the fuel cell only at night.

The sensitivity analysis showed that reducing PV array costs from $5/Wp to $2/Wp reduces levelized cost by $0.20/kWh (32%). The effect of using the engine at night plus as daytime backup reduces cost by $0.08/kWh (11%), increases availability by 1.3 percent and reduces battery size by 49 percent over using the engine at night only.

Assuming 100% equipment availability, the results indicate that the best PV/fuel cell system with low initial cost, low energy cost, high availability and low battery storage utilizes a 3 kW fuel cell (operating at night with fuel cell having priority over battery and as daytime backup), a 111.5 m2 PV array and 67.0 kWh of battery storage. If the fuel cell cannot be kept on standby all day to operate as a daytime backup, then a 6 kW fuel cell with 111.5 m2 of PV array and 192.6 kWh of battery storage hybrid is needed. For the preferred case, on a yearly basis, the PV array provides 23,140 kWh and the fuel cell provides 9,196 kWh. If the fuel cell cannot be used as a daytime backup, the PV array provides 21,540 kWh and the fuel cell provides 7,839 kWh.

EXHIBIT 5-7

TUNISIAN VILLAGE
50 kWh/DAY PV/FUEL CELL HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY PV $5/Wp PV $2/Wp	0 0	0 0	172.9 172.9	5 5	559.4 559.4	1.27 0.84	99.6 99.6	214760 145600
PV/FUEL CELL ONLY, WITH IT CHARGING BATTERY	3.0 6.0	3193 6419	0 0	1 1	29.7 84.9	0.41 0.63	40.8 72.8	19710 24770
same as above + 5 DAYS OF BATTERY STORAGE	3.0 6.0	3339 6419	0 0	5 5	148.6 42.3	0.54 0.60	61.0 97.3	39340 31640
PV/FUEL CELL WITH ENGINE OPERATING ALL THE TIME	3.0 6.0	2785 6116	43.3 8.3	1 1	28.4 8.4	0.45 0.58	64.7 69.8	49820 30570
PV/FUEL CELL WITH ENGINE OPERATING AT NIGHT, ENGINE PRIORITY OVER BATTERY	3.0 6.0	1181 2316	111.5 103.8	3 3	201.1 192.6	0.71 0.79	98.7 99.2	124665 126250
same as above + ENGINE OPERATING AS DAYTIME BACKUP	3.0 6.0	2396 4596	111.5 103.8	1 1	67.0 64.2	0.63 0.77	100.0 100.0	117700 116800
same as above with PV $2/Wp	3.0 6.0	2396 4596	111.5 103.8	1 1	67.0 64.2	0.43 0.58	100.0 100.0	117700 116800
DIESEL OR GASOLINE REFERENCE GENERATOR	6.0	3465	0	0	0	0.86	100.0	16250

* peak output W/m^2

5.1.7 Recommendations for Tunisian Village Power Application

The PV hybrid system configuration and operating protocol selected for the detailed conceptual design are as follows:

- PV/wind

  - 59.4 square meter PV array (5.9 kWp)
  - 202.7 kWh of battery storage
  - Initial capital of $117,000
  - Energy cost from the system of $0.67/kWh
  - System resource availability of 99.6 percent.

- PV/diesel generator

  - The engine generator set is used as the primary power source at night. The PV and battery are the primary power sources during the day and the engine is used only as a backup during daytime hours.
  - 4 kW diesel generator operating between 50 percent and 80 percent of nameplate rating
  - 110 square meter PV array (11 kWp)
  - 66.6 kWh of battery storage
  - Initial capital cost of $104,000
  - Energy cost from the system of $0.79/kWh
  - System resource availability of 99.4 percent.

- PV/fuel cell

  - The fuel cell is used exactly as the diesel generator above
  - 3 kW fuel cell generator
  - 111.5 square meter PV array (11.2 kWp)
  - 67.0 kWh of battery storage
  - Initial capital cost of $118,000
  - Energy cost from the system of $0.63/kWh
  - System resource availability of 100 percent.

For all the above systems it has been assumed that the equipment is 100 percent available. Equipment reliability will be discussed in Section 5.3.

5.2 PV Hybrid System Assesement for Village Power Application in Utirik Island in the Marshall Islands

Utirik Island is located in the Marshall Islands Trust Territory, at latitude 11°15'N and longitude 169°49'E. The purpose of this section is to present the results obtained from the evaluation of several PV/wind hybrid systems and select a system for conceptual design.

5.2.1 Village Energy Requirements

Utirik Island requires approximately 20 kWh/day of electric energy. The loads are shown in Exhibit 5-8. The system must be able to provide 20 kWh/day of electrical energy at 110 V DC with 99 percent, or better, availability. The daily load distribution and its seasonal variation is shown in Exhibit 5-9. The peak load is 3.47 kW.

5.2.2 Village Resource Availability

Insolation for Utirik is shown in Exhibit 5-10. Corresponding wind speed data is shown in Exhibit 5-11.

5.2.3 PV Hybrid System Evaluated

The hybrid system evaluated for Utirik was a PV/wind system supplying DC power. In order to compare the relative merits of a PV/wind system, a PV/battery system was also evaluated. Input data are shown in Exhibit 5-12.

5.2.4 PV/Wind Hybrid System Evaluation

Several PV/wind system configurations were evaluated to find the least cost system with availability of at least 99 percent. A summary of the results is shown in Exhibit 5-13.

The analysis showed that at least three days equivalent of battery storage was needed to ensure that availability was greater than 99 percent. The analysis also considered the following cost and performance alternatives:

- Effect of reducing PV array cost from \$5/Wp to \$2/Wp
- Effect of including a spare wind turbine and generator

The sensitivity analysis showed that reducing PV costs from \$5/Wp to \$2/Wp reduced levelized costs by \$0.20/kWh (36%). The inclusion of a spare wind turbine and generator increased costs by about \$0.10/kWh.

Assuming 100% equipment availability, the results indicate that the best PV/wind system in terms of low initial cost, low energy cost, high availability, and low battery storage utilizes a 3.5 kW wind generator, a 22.6 m^2 PV array and 85.8 kWh of battery storage. This system has an initial cost of \$42,000 and a levelized busbar electricity cost of \$0.56/kWh. On a yearly, basis the PV array provides 4329 kWh and the wind generator 7030 kWh.

EXHIBIT 5-8

ELECTRICAL LOADS FOR UTIRIK ISLAND

Load Devices	No. of Units	Approximate Power per Unit	Demand Time Per Day	Approximate Energy Consumption Per Day
Incandescent Lights	76	7 Watts	8 Hrs	4,256 W-Hr
Fluorescent Lights	95	24 Watts	4 Hrs	9,120 W-Hr
L.P. Sodium Vapor Lights	5	30 Watts	11 Hrs	1,650 W-Hr
Refrigerators	6	37.5 Watts	24 Hrs	5,400 W-Hr
Ventilation Fan	7	26.4 Watts	8 Hrs	1,479 W-Hr
Medical Sterilizer	1	600 Watts	.01 Hrs	6 W-Hr
Medical Exam Light	1	41 Watts	.03 Hrs	12 W-Hr
Battery Charger	1	40 Watts	10 Hrs	400 W-Hr
Estimated total energy consumption per day				22,323 W-Hr

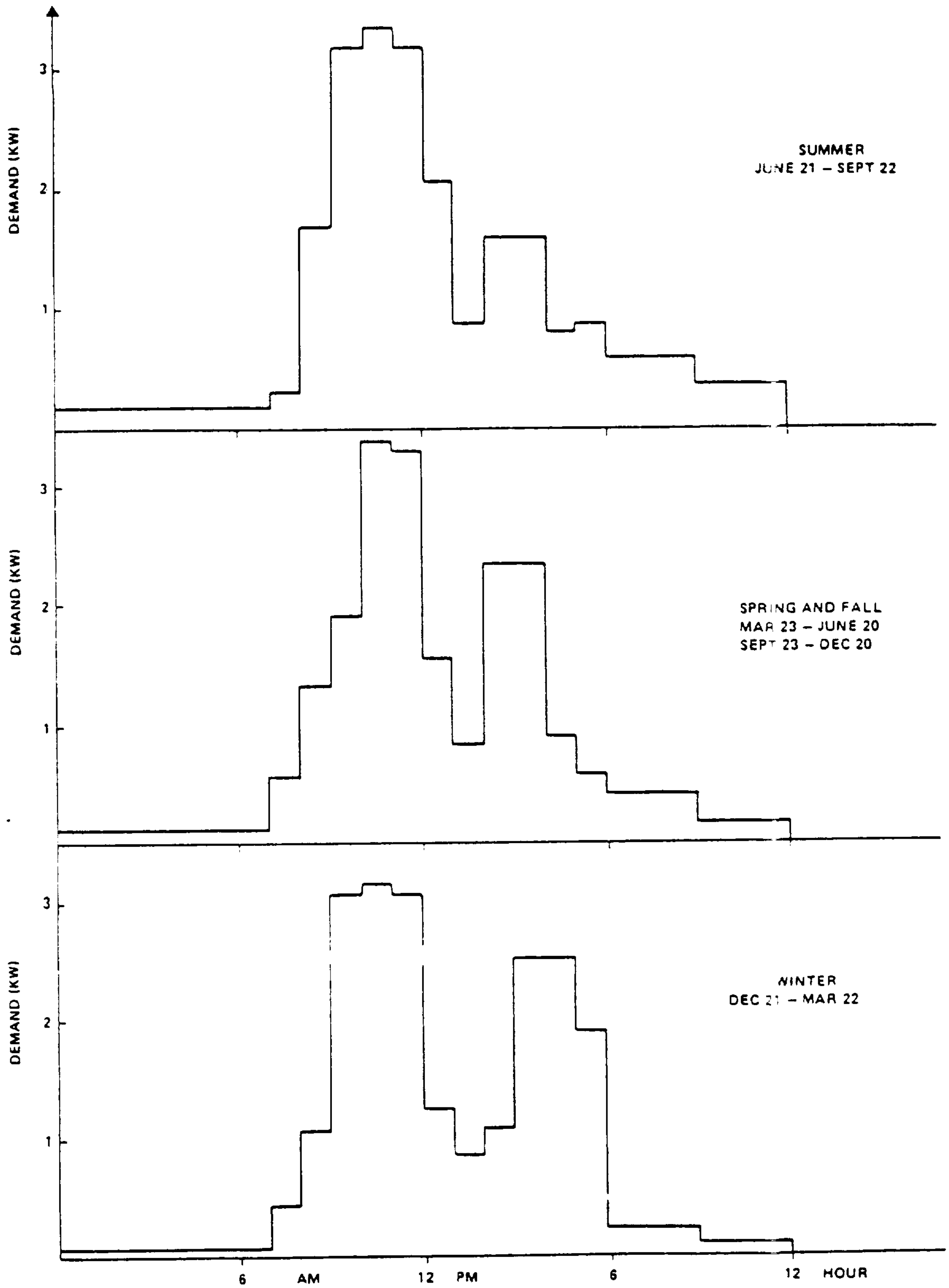


EXHIBIT 5-9: SEASONAL DAILY LOAD DISTRIBUTION FOR UTIRIK ISLAND VILLAGE POWER APPLICATIONS

EXHIBIT 5-10

SOLAR INSOLATION DATA FOR THE ISLAND OF UTIRIK

- LOCATION - UTIRIK ISLAND
- LATITUDE - 11.15°N
- GROUND REFLECTANCE - 0.25
- ARRAY TILT ANGLE - 11.15

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
CLEARNESS INDEX	.545	.571	.611	.582	.584	.504	.525	.502	.498	.538	.546	.571

Source: Calculated from average monthly insolation values provided by NASA/LERC

EXHIBIT 5-11

WIND SPEED DATA FOR THE ISLAND OF UTIRIK

- Measurement Height - 10m
- Hourly mean wind speed (m/s)*

Hour	1	7	13	21
Speed	4	8.5	12	7.0

- Monthly mean wind speed (m/s)**

J	F	M	A	M	J	J	A	S	O	N	D
8.99	9.91	8.99	8.07	7.15	6.23	5.31	4.39	5.31	6.23	7.15	8.07

*Source: Mikkail, A. "Wind Power for Developing Nations," SERI DE81 025792, page 29.

**Source: U.S. Department of Energy. Territorial Energy Assessment. Final Report, DOE/CP-0005/1, December 1982, page 140.

EXHIBIT 5-12

PV HYBRID SYSTEMS INPUT DATA FOR UTIRIK ISLAND

- PV Array Input Data

Efficiency, (%)	- 10
Cost, ($/Wp)	- 5 and 2
O&M ,(% of Total PV installation cost)	- 1%
Balance of System Cost, ($/Wp)	- 2 and 1
Life, (years)	- 20

- Battery Input Data

Efficiency, (%)	- 85
Charging Rate, (%)	- 25
Discharge Rate, (%)	- 25
Depth of Discharge, (%)	- 70
Cost, ($/kWh)	- 150
Life, (years)	- 10
Balance of system cost, (kWh)	- 17

- Wind Generator Input Data

Size (kW)	Cut in Speed (m/s)	Rated Speed [illegible]	Cut out Speed (m/s)	Cost -($) (includes Tower & 20% installation)	O&M -(% of Total Cost)	Hub Height	Li (Ye
1.2	4.0	11.0	13.4	6720	2.5	20	[illegible]
1.5	4.0	11.0	14.0	8040	2.5	20	[illegible]
1.8	3.6	12.0	17.9	11040	2.5	20	[illegible]
3.5	4.5	11.2	13.0	12084	2.5	20	[illegible]
6.0	4.0	11.6	27.7	22800	2.5	20	[illegible]

All wind generators shown above were de-rated 15% from their rated kW power output to account for yawing and acceleration losses.

EXHIBIT 5-12

PV HYBRID SYSTEM COMPONENT INPUT DATA (CONCLUDED)

- Miscellaneous Input Data

Project life (years)	-	20
Debt Cost (%)	-	5
Debt Ratio	-	1
Sizing period (days)	-	30

A constant dollar analysis in 1983 dollars was used for cost comparisons.

EXHIBIT 5-13

UTIRIK ISLAND
20 kWh/DAY PV/WIND HYBRID SYSTEM ANALYSIS RESULTS

SYSTEM CONFGRT.	ALTERNATE. GENERATOR SIZE (kW)	FUEL USED (gal)	PV ARRAY* SIZE (m**2)	DAYS OF BATTERY STORAGE	BATTERY SIZE (kWh)	LEVELIZED BUSBAR COST (1983$) ($/kWh)	RESOURCE AVAILABILITY (equipment 100% available) (%)	INITIAL CAPITAL COST (1983$)
PV ARRAY ONLY PV $5/Wp	0	0	49.4	3	110.0	0.67	99.2	52520
PV $2/Wp	0	0	49.4	3	110.0	0.45	99.2	32770
PV/WIND	1.2	0	37.3	3	94.0	0.63	99.5	48440
	1.5	0	34.9	3	92.0	0.62	99.5	47690
	1.8	0	35.0	3	84.4	0.64	99.5	49720
	3.5	0	22.6	3	85.8	0.56	99.5	42280
	6.0	0	4.3	3	84.5	0.55	99.1	39900
same as above + 1 SPARE WIND GENERATOR	1.2	0	37.3	3	94.0	0.67	99.5	51520
	1.5	0	34.9	3	92.0	0.68	99.5	52310
	1.8	0	35.0	3	84.4	0.73	99.5	56710
	3.5	0	22.6	3	85.8	0.66	99.5	49830
	6.0	0	4.3	3	84.5	0.75	99.1	54530
same as above + PC COST AT $2/Wp	1.2	0	37.3	3	94.0	0.50	99.5	37240
	1.5	0	34.9	3	92.0	0.52	99.5	38150
	1.8	[illegible]	[illegible]	3	84.4	0.57	99.5	42420
	3.5	0	22.6	3	85.8	0.56	99.5	40480
	6.0	0	4.3	3	84.5	0.73	99.1	52725
same as above NO SPARE WIND GENERATOR	1.2	0	37.3	3	94.0	0.45	99.5	33520
	1.5	0	34.9	3	92.0	0.46	99.5	33750
	1.8	0	35.0	3	84.4	0.48	99.5	35720
	3.5	0	22.6	3	85.8	0.46	99.5	33250
	6.0	0	4.3	3	84.5	0.53	99.1	38280

* peak output 100 W/m^2

5.3 Operational Availability of Power Systems

The previous section determined the PV array, battery and alternate generator sizes for satisfying the power demand, at the specified availability, assuming that the hybrid system components were functioning normally. The purpose of this section is to estimate the degree of redundancy necessary so that operational availability is at, or above, specifications. Operational availability is defined as percent of time demand is fully satisfied, given uncertainties associated with resource availability and equipment reliability and maintainability.

Exhibit 5-14 shows a simplified PV hybrid system block diagram to be used for assessing operational availability. At present, no mathematical procedure, other than Monte Carlo simulation, exists for estimating the operational availability of such a complex system. The complexity of the system derives from the uncertainties associated with resource availability and component reliability and their interactions. For example, the probability of failure of a wind turbine is a function of windspeed, degree of turbulence and other wind-related factors. While Monte Carlo simulation is a feasible method, it requires substantial computer time, because 10,000 or more simulations are needed to obtain reasonably accurate estimates. Since simulating one year of operation requires ten seconds of computer time, estimating operational availability will require about 28 hours, which is prohibitively expensive. Thus, use of Monte Carlo simulation was not considered.

The simplified approach used was to ensure that the availability of each major hybrid system component was higher than the specified system operational availiability, so that the joint operational availability (product of the components, in this case) is as specified. For example, if the required operational availability was 99 percent, each major component (PV array, battery, alternate generator and control system) had to have an availability higher than 99 percent. The rationale behind this approach was that since all the components have to be functioning, each component must have an operational availability higher than the system operational availability. The following sections describe the degree of redundancy needed for ensuring that equipment availability is adequate.

5.3.1 Photovoltaic Module Redundancy

The nominal design of the PV array (Section 5.1 and 5.2) for the hybrid systems does not include an allowance for the power degradation of the array due to random cell failures over the assumed twenty year life of the system. The following analysis estimates the number of redundant modules necessary to ensure that adequate power is available throughout the system life.

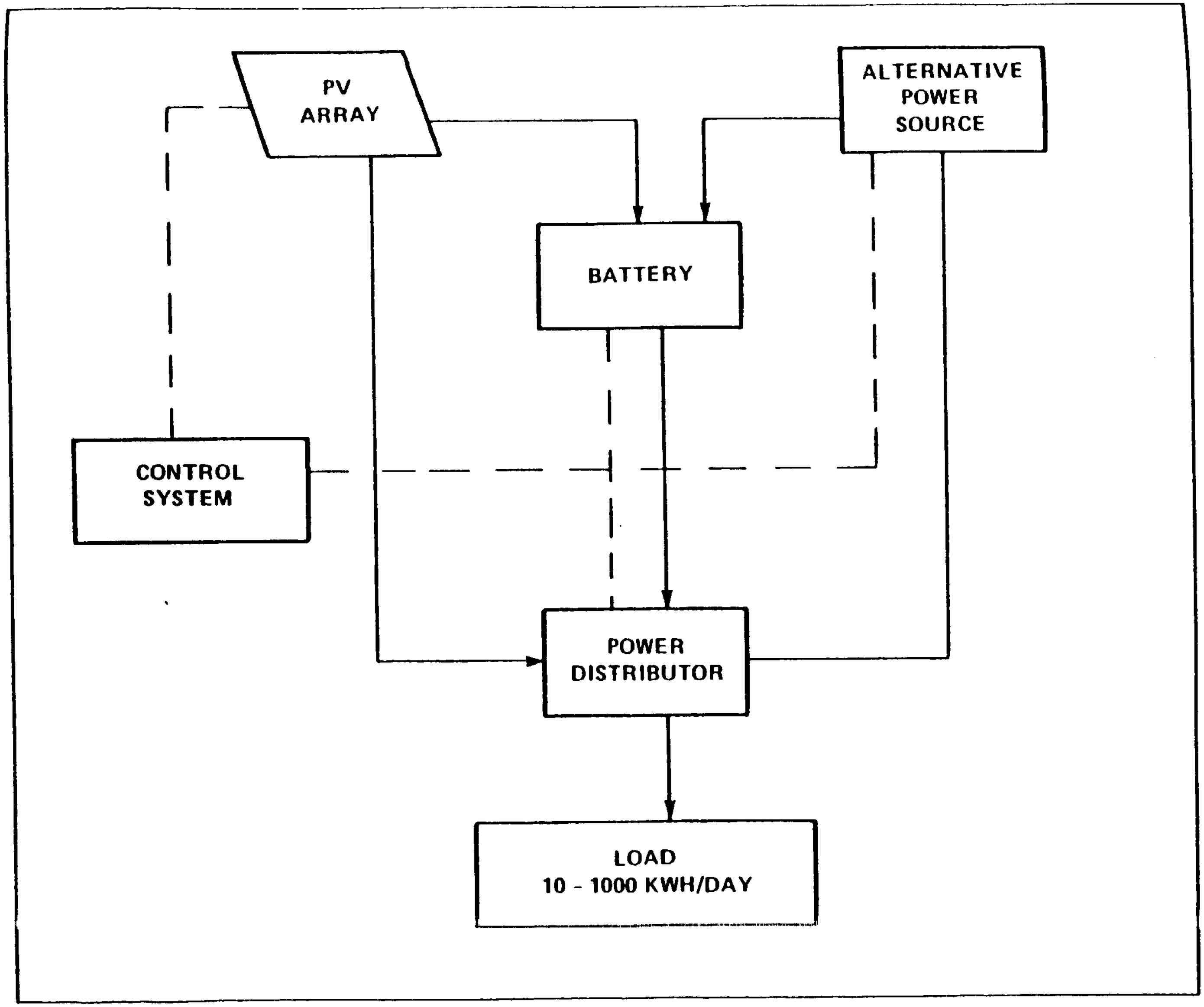


EXHIBIT 5-14: SIMPLIFIED HYBRID SYSTEM DIAGRAM FOR ASSESSING OPERATIONAL AVAILABILITY

The predicted degradation is based on the approach in the JPL handbook of PV system circuit design.[1] The computational procedure was used to examine the I-V curve for every possible array failure configuration, find the peak power and compute the probability of the failure. Peak power is multiplied by the probability and the sum of the products gives the expected peak power value. The analysis assumes that no modules will be replaced during the 20-year system life, except perhaps in the first year under the system warranty, when the failure rate might be higher due to "infant mortality". The analysis was used to compute the number of redundant modules needed in the array to satisfy expected power demand at the end of the 20 year system life.

The power prediction is based on the Solar Power Corporation module (Model No: G12-361CT, peak power output = 37 W, and 36 cells in series per module). At its current stage of development, the module has an efficiency of about 7 percent. The cell efficiency is expected to increase as the technology progresses. The increased efficiency would be reflected in the array size selected to meet the load; however, for the degradation analysis, the present-day efficiency was used for convenience because the entire I-V curve can be taken from commercially available literature. The results apply to higher efficiency cells as well because the degradation rate is independant of the cell efficiency.

The nominal array configuration used in this analysis were as follows:

- Tunisian village
  - PV/wind - 14 branch currents (bc) x 12 modules in series per bc x 1 module per series block (p)
  - PV/diesel and PV/fuel cell - 25 bc x 12 s x 1 p

- Utirik, Island
  - PV/wind - 5 bc x 12s x 1 p

The configuration was selected so that peak power trackers and ground fault detectors could be used. The degradation analysis showed that after 20 years 92.7 percent of design peak power output would be available from the array. Thus, the array size should be increased by 1/0.927 to ensure that required peak power is available after 20 years.

The degradation analysis for the Tunisian village and Utirik showed that the systems will experience a power degradation of no more than 7.3 percent over the 20-year system life. This estimate is based on a cell failure rate of one per 10,000 years, which is the failure rate adopted by JPL and substantiated by field experience. Exhibit 5-15 summarizes the results of the degradation analysis. For

1 Jet Propulsion Laboratory, "Workshop on FlatPlate PV Module and Array Circuit Design Optimization", May 19-20, 1980.

EXHIBIT 5-15

PV ARRAY REDUNDANCY REQUIREMENTS

SYSTEM	REQUIRED PEAK POWER (WATTS)*	ARRAY WITHOUT REDUNDANCY				ARRAY WITH REDUNDANCY TO OFFSET DEGRADATION			
		MODULE ARRANGEMENT	PEAK POWER (WATTS)		PEAK POWER AVAILABILITY AFTER 20 YEARS (%)#	MODULE ARRANGEMENT	PEAK POWER (WATTS)		PEAK POWER AVAILABILITY AFTER 20 YEARS (%)#
			DESIGN	AVAILABLE@ AFTER 20 YEARS			DESIGN	AVAILABLE@ AFTER 20 YEARS	
TUNISIAN VILLAGE									
1. PV/WIND	5940	14bc x (12s x 1p)**	6290	5831	98	14bc x (13s x 1p)	6814	6317	106
2. PV/DIESEL	11000	25bc x (12s x 1p)	11232	10412	95	25bc x (13s x 1p)	12168	11280	103
3. PV/FUEL CELL	11115	25bc x (12s x 1p)	11232	10412	94	25bc x (13s x 1p)	12168	11280	101
Utirik, ISLAND									
PV/WIND	2260	5bc x (12s x 1p)	2246	2082	92	5bc x (13s x 1p)	2434	2256	100

* Equals Array Area calculated in Section 4.1 - Times Module Peak Output

@ 92.7 percent of design peak output

\# ((Peak Power after 20 years)/(Required Peak Power)) x 100

** The module arrangement is described by the number of branch circuits (bc), the number of modules (p) in a series block and the number of series blocks (s) connected in series to form a branch circuit.

the array configuration, with and without redundancy, the exhibit shows the design peak power, power availability after 20 years and the percent of required peak power available after 20 years. The redundant modules (one per subarray) have been added to each branch circuit to ensure that after 20 years, the string voltage will exceed battery voltage.

5.3.2 Battery Redundancy

Compared to PV modules, batteries have higher failure rates (mean time between failures, (MTBF) is about 2 million hours per battery cell). Thus, unlike the PV array design case, the battery redundancy analysis calculates the number of spare batteries that must be kept on hand to support on-demand battery maintenance.

The procedure used to calculate the number of spares needed assumes that the battery cells exhibit an exponential failure mode with a constant failure rate,(λ=1/MTBF) during its useful life. It is also assumed that a failed battery is replaced almost immediately. Using these assumptions, it can be shown that the survival probability of a series string of N cells, with S spares on-site and a battery reorder interval of "t" is given by:

$$P(s) = e^{-N\lambda t} \sum_{i=o}^{S} \left[(N\lambda t)^{i} / i! \right]$$

Thus, the value of S corresponding to a survival probability greater than 99 percent would be the number of spares needed to ensure battery availability of greater than 99 percent.

For the PV hybrid system for Tunisia and Utirik Island, a battery reorder interval of six months was assumed (i.e. t = 4380 hours). The following computation for the PV/wind hybrid for Tunisia demonstrates the use of the equation described previously:

Battery storage required	= 202.7 kWh
Battery string voltage	= 120 V
Battery capacity	= 2.652 kWh (221 Ah)
Battery voltage	= 12 V
Number of cells per battery	= 6

Total number of batteries in series = $\frac{120}{12}$ = 10 batteries

No. of parallel strings required = $\frac{202.7}{2.652 \times 10}$ = 7.643 = 8

Battery array configuration = 8 parallel strings of batteries, each with 10 batteries in series

Each parallel string must have an availability greater than 99 percent. For the above case:

$N = 10$
$\lambda = 6/(2\times10^6) = 3 \times 10^{-6}$ (since there are 6 cells/battery)
$t = 4380$ hours

$$P_0 = \exp(N\lambda t) = \exp(-20 \times 3 \times 10^{-6} * 4380) = 0.769$$

$$P_1 = \exp(N\lambda t) * \frac{N\lambda t}{1} = 0.769 * 0.2638 = 0.202$$

$$P_2 = \exp(N\lambda t) * (N\lambda t)^2/2 = 0.769 * 0.035 = 0.027$$

Availability when two spares are sufficient $= P_0 + P_1 + P_2$

$= 0.998$

Since availability is greater than 99 percent, two spares per string for a total of 16 batteries are needed.

Exhibit 5-16 shows the results of the battery redundancy computations for all the PV hybrid systems. In each case, since labor is assumed available at the site, redundant batteries are not a part of the battery array; instead, the failed batteries are replaced with the spares maintained on-site.

5.3.3 Alternate Generator Redundancy

A continuous transition Markov process is used to represent random failures of the alternate generator. The alternate generator at any given moment must be in one of two discrete states as shown in Exhibit 5-17:

- The "U" or upstate in which the unit is ready and available for use; and

- The "D" or down state in which the unit is unavailable for use.

For the representation in Exhibit 5-17, availability of the generator is given by the probability that the "U" state will occur. That is:

$$A = \mu/(\lambda+\mu)$$

$$A = MTBF/(MTBF + MDT)$$

EXHIBIT 5-16

BATTERY REDUNDANCY ANALYSIS SUMMARY

HYBRID SYSTEM	STORAGE REQUIREMENTS kWh	BATTERY SPECIFICATION AH, V (20 hour rate)	BATTERY CONFIGURATION		SPARES REQUIRED ON-SITE (BATTERIES)
			Series×Parallel	kWh	
TUNISIAN VILLAGE					
PV/Wind	202.7	221, 12	10 x 8	212	16
PV/Diesel	66.6	221, 12	10 x 3	80	6
PV/Fuel Cell	67.0	221, 12	10 x 3	80	6
Utirik					
PV/Wind	85.8	221, 12	10 x 4	106	8

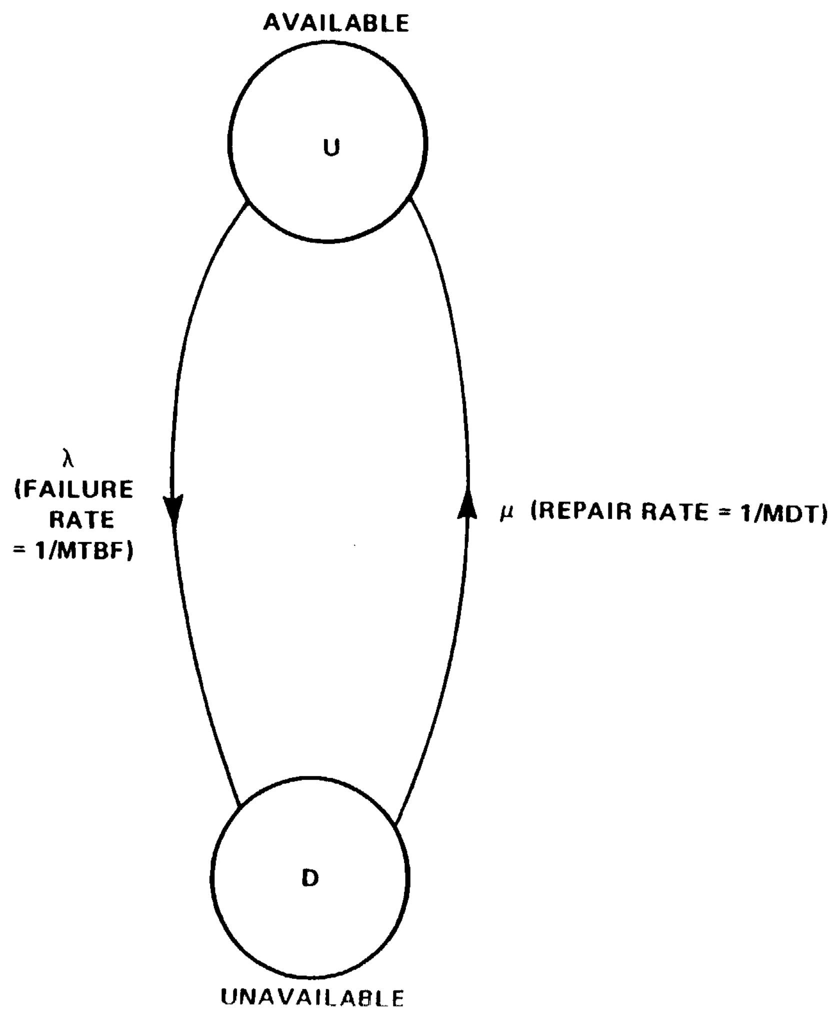


EXHIBIT 5-17: MARKOV REPRESENTATION OF THE ALTERNATE GENERATOR

where μ is the repair rate (inverse of MDT, the mean down time) and λ is the failure rate (inverse of MTBF, mean time between failures). Similarly, the probability that the "D" state will occur is given by $\lambda/(\lambda+\mu)$.

For example, if a diesel generator has a MTBF of 3500 hours and a MDT of one week (168 hours), equipment availability is:

$$A = 3500/3500 + 168)$$

$$A = 0.954$$

Next consider the availability of an identical standby generator. The state space diagram for this system is shown in Exhibit 5-18.

The probability that both the primary generator and the alternate generator are down is given by:

$$\begin{aligned} P_o &= (\text{Probability that the primary generator is down}) \times \\ &\quad (\text{Probability that the standby generator is down}) \\ &= (\lambda/(\lambda+\mu))2 \end{aligned}$$

Therefore, the availability of at least one generator is given by $(1-P_o)$. That is:

$$A = 1 - (\lambda/(\lambda+\mu))^2$$

$$A = 1 - \left[\frac{MDT}{MTBF+MDT}\right]^2$$

In general, it can be shown that if there is one primary generator and N identical standby generators, availability is given by:

$$A = 1 - \left[\frac{MDT}{MTBF+MDT}\right]^{N+1}$$

For example, if a diesel generator (MTBF = 3500, MDT = 168 hours) has a standby generator, then availability is:

$$A = 1 - \left[\frac{168}{3500+168}\right]^2 = 0.998$$

The effect of redundancy is immediately apparent when the above estimate is compared to the availability without a standby generator (0.954).

Exhibit 5-19 shows the variation of equipment availability with varying values of MTBF and MDT for zero and 1 standby unit.

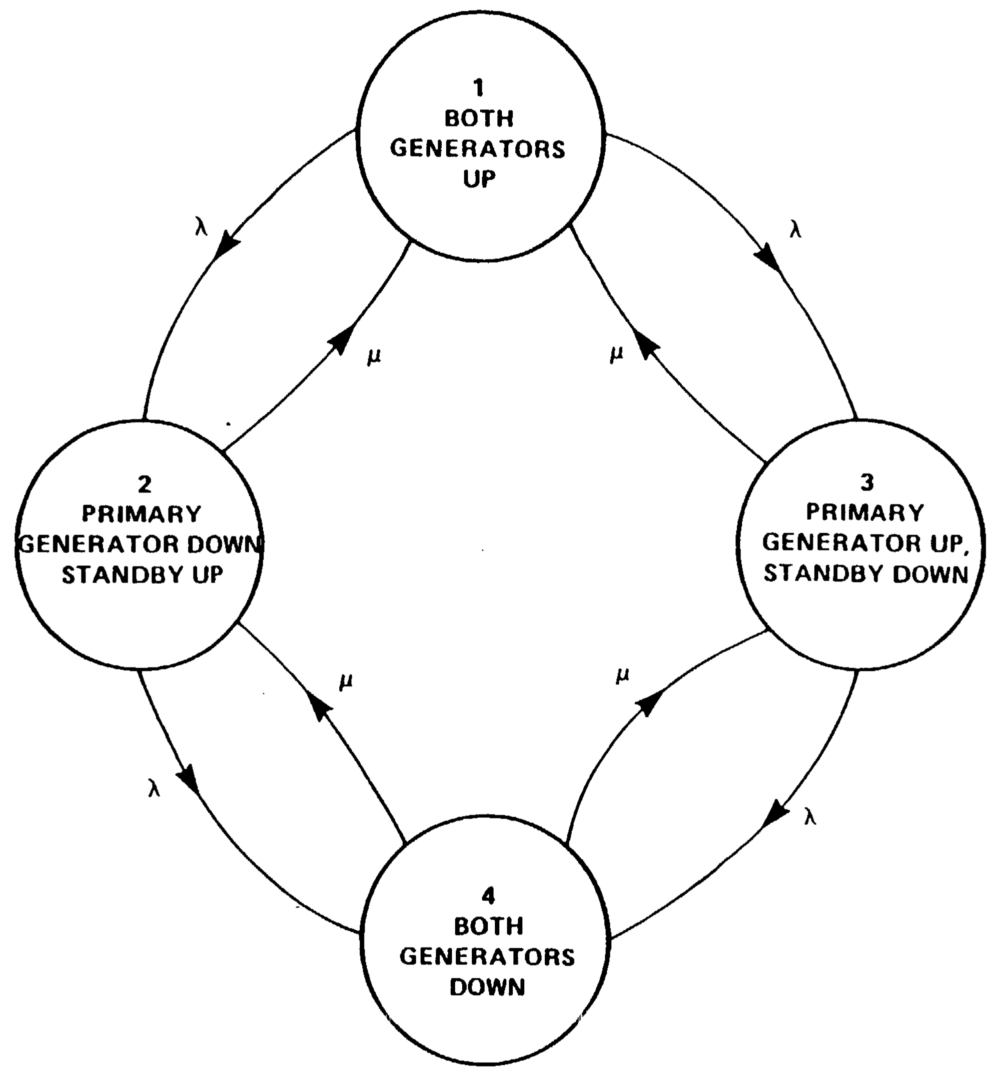


EXHIBIT 5-18: STATE-SPACE DIAGRAM WHEN STANDBY GENERATOR IS AVAILABLE

For a diesel generator which typically has a MTBF of about 3000 hours, one standby unit will be required if mean down time is about one week. However, if repairs can be accomplished in a day, no standby generator will be required. For the PV/diesel hybrid system design for the Tunisian village, since the power plant is located in a village, a MDT of one week will be assumed, thus requiring one standby generator.

Current operating experience with small wind machines indicate that down time is about 10 percent and wind machine plant factor is about 8 to 9 percent[1]. Thus, adequate spares would have to be maintained on-site to ensure high availability. High reliability wind turbines for remote operations have been developed by North Wind.

North Wind Model HR2 has been specifically designed to supply power at remote sites under harsh environmental conditions. The MTBF of the HR2 machine is calculated at 105,000 hours. The equipment availability of such a machine with no standby is 99.8 percent, for a MDT of one week. At a MDT of one month the availability is still greater than 99 percent. Availability drops below 99 percent only if MDT is above two months.

Fuel cells are expected to be highly reliable power systems with an operational life of 5 years without refurbishment[2]. Periodic maintenance is required only after 8000 hours of operation. Periodic maintenance will not require more than 3 hours to accomplish. Thus, ensuring high fuel cell reliability will require only stocking of normal spares as recommended by the manufacturer.

In addition to spares for the alternate generator and batteries, control and monitoring components should have the requisite spares as recommended by the manufacturer. The procedure described in Section 5.3.2 on battery redundancy determination can be used to estimate number of spares needed.

5.4 Summary of System Configurations for Detailed Conceptual Designs

Exhibit 5-20 shows the component sizes to be used for the detailed conceptual designs for the Tunisian village and Utirik. The configurations shown in the exhibit allow for resource availability uncertainties as well as equipment reliability and maintainability.

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1 Prichett, Wilson, "Survey of Cost and Operating Experiences for Small Wind Machines Connected to Rural Electric Lines in the United States," National Rural Electric Cooperative Association, Washington, D.C.

2 Eklund, L.G., On-site 40 kW Fuel Cell Power Plant: Specification for Field Test Model, United Technologies Power Systems, May, 1982.

EXHIBIT 5-19

VARIATION OF EQUIPMENT AVAILABILITY WITH MTBF AND MDT

	EQUIPMENT AVAILABILITY (PERCENT)							
MTBF (Hours)	3000		5000		10,000		20,000	
Number of Standby Units	0	1	0	1	0	1	0	1
Mean Down Time								
1 Day	99.2	100.0	99.5	100.0	99.8	100.0	99.9	100.0
1 Week	94.7	99.7	96.7	99.9	98.3	100.0	99.9	100.0
1 Month	80.6	96.3	87.4	98.4	93.3	99.5	96.5	99.9
3 Months	58.1	82.5	69.8	90.9	82.2	96.8	90.3	99.0
6 Months	41.0	65.2	53.6	78.5	69.8	90.9	82.2	96.8
1 Year	25.5	44.5	36.3	65.2	53.3	71.6	69.5	90.6

Equipment Availability = 1 - (1/(1 + (MTBF/MDT)**(N+1))) * 100

Where MTTF = Mean time to failure (hours)
MDT = Mean down time (hours)
= Time to detect malfunction + time to obtain spares
+ Time to visit site + repair time
N = Number of standby units.

5.5 Sensitivity to Demand Uncertainties

The previous analyses took into consideration random variations in insolation and wind, and equipment reliability. Hourly demand was assumed to be non-random. However, hourly demand can also vary from the mean value assumed for sizing purposes. Demand could deviate from the mean in a number of ways. For example:

- Demand could be less than expected
- Demand could be greater than expected
- Demand could randomly vary around the mean value

The purpose of the following analyses is to determine the robustness of the designs under each of the above conditions. Robustness testing is performed for the following:

(1) Demand 20 percent less than the mean

(2) Demand 20 percent greater than the mean

(3) Demand varies randomly $\pm$20 percent about the mean

5.5.1 Effect of Twenty Percent Demand Change

Exhibits 5-21 to 5-24 shows the results of the first two cases for the PV hybrid systems for the Tunisian village and Utirik. These analyses were conducted without considering the additional PV modules used for redundancy since at the end of the 20 year period, these modules would have failed.

The exhibits show, as expected, that decrease in demand either increases availability or produces no change when compared to the design case. However, the PV array is oversized 20 to 50 percent and the battery is oversized 18 to 35 percent.

When demand increases by 20 percent, availability drops 4 to 9 percentage points. The most seriously affected is the PV/wind hybrid for the Tunisian village whose availability drops from 99.7 to 90.8 percent. If availability is to be above 99 percent for each system, the array size should be increased by 24 to 45 percent and the battery size should be increased by 3 to 17 percent for the Tunisian village. Unexpectedly, the battery size for Utirik decreases from 106 kWh to 104. However, this is somewhat misleading since the actual battery size required for Utirik was 85 kWh, even though, due to practical considerations, the design provided for a 106 kWh battery.

EXHIBIT 5-20

DETIALED DESIGN CONFIGURATION

HYBRID SYSTEM	PV ARRAY ARRANGEMENT*	BATTERY			ALTERNATE GENERATORS	
		CAPACITY PER BATTERY (Ah,V)	ARRANGEMENT PARALLEL X SERIES	SPARES	SIZE (kW)	SPARES
TUNISIAN VILLAGE						
PV/Wind	14bc x 13s	221, 12	8 x 10	16	10	Manufacturers Recommendation
PV/Diesel	25bc x 13s	221, 12	3 x 10	6	4	One Spare
PV/Fuel Cell	25bc x 13s	221, 12	3 x 10	6	3.7	Manufacturers Recommendation
Utirik						
PV/Wind	5bc x 3	221, 12	4 x 10	8	3.5	Manufacturers Recommendation

* bc = branch circuits

s = number of modules in series per branch circuit

EXHIBIT 5-21

EFFECT OF DEMAND VARIATIONS ON THE
PV/WIND HYBRID SYSTEM FOR THE TUNISIAN VILLAGE

DEMAND PROFILE	PV ARRAY SIZE m^2	BATTERY SIZE kWh	ALTERNATE GENERATOR SIZE kW	FUEL CONSUMPTION PER YEAR GALLONS	ENERGY DEFICIT kWh/YEAR	RESOURCE AVAILABILITY (ASSUMING 100 PERCENT EQUIPMENT AVAILABILITY) PERCENT
• Design Demand Profile	62.2	212	10	0	36	99.7
• 20% Increase in Demand						
- For no Change in Sys. Configuration	62.2	212	10	0	1461	90.8
- For >99% Resource Availability	88.4	249	10	0	142	99.3
- Percent Increase in Component Sizes	42	17	0	0	---	---
• 20% Decrease in Demand						
- For no Change in System Configuration	62.2	212	10	0	0	100.0
- For >99% Resource Availability	30.3	173	10	0	84	99.1
- Percent Decrease in Component Sizes	51	18	0	0	---	---

EXHIBIT 5-22

EFFECT OF DEMAND VARIATIONS ON THE PV/DIESEL HYBRID SYSTEM FOR THE TUNISIAN VILLAGE

DEMAND PROFILE	PV ARRAY SIZE m^2	BATTERY SIZE kWh	ALTERNATE GENERATOR SIZE kW	FUEL CONSUMPTION PER YEAR GALLONS	ENERGY DEFICIT kWh/YEAR	RESOURCE AVAILABILITY (ASSUMING 100 PERCENT EQUIPMENT AVAILABILITY) PERCENT
• Design Demand Profile	111	80	4	1093	11	99.8
• 20% Increase in Demand						
- For no Change in System Configuration	111	80	4	1239	228	97.0
- For >99% Resource Availability	138	82	4	1169	69	99.9
- Percent <u>Increase</u> in Component Sizes	24	3	0	-6	---	---
• 20% Decrease in Demand						
- For no Change in System Configuration	111	80	4	745	13	99.8
- For >99% Resource Availability	89	54	3	941	27	99.3
- Percent <u>Decrease</u> in Component Sizes	20	33	25	-26	---	---

EXHIBIT 5-23

EFFECT OF DEMAND VARIATIONS ON THE
PV/FUEL CELL HYBRID SYSTEM FOR THE TUNISIAN VILLAGE

DEMAND PROFILE	PV ARRAY SIZE m^2	BATTERY SIZE kWh	ALTERNATE GENERATOR SIZE kW	FUEL CONSUMPTION PER YEAR GALLONS	ENERGY DEFICIT kWh/YEAR	RESOURCE AVAILABILITY (ASSUMING 100 PERCENT EQUIPMENT AVAILABILITY) PERCENT
• Design Demand Profile	111	80	3	3036	0	100.0
• 20% Increase in Demand						
- For no Change in System Configuration	111	80	3	3148	201	97.0
- For >99% Resource Availability	141	83	3	3066	47	99.3
- Percent Increase in Component Sizes	27	4	0	-3	---	---
• 20% Decrease in Demand						
- For no Change in System Configuration	111	80	3	2936	0	100.0
- For >99% Resource Availability	85	52	3	3030	0	100.0
- Percent Decrease in Component Sizes	23	35	0	-3	---	---

EXHIBIT 5-24

EFFECT OF DEMAND VARIATIONS ON THE PV/WIND HYBRID SYSTEM FOR UTIRIK

DEMAND PROFILE	PV ARRAY SIZE m^2	BATTERY SIZE kWh	ALTERNATE GENERATOR SIZE kW	FUEL CONSUMPTION PER YEAR GALLONS	ENERGY DEFICIT kWh/YEAR	RESOURCE AVAILABILITY (ASSUMING 100 PERCENT EQUIPMENT AVAILABILITY) PERCENT
• Design Demand Profile	22	106	3.5	0	24	99.6
• 20% Increase in Demand						
- For no Change in System Configuration	22	106	3.5	0	313	96.0
- For >99% Resource Availability	32	104	3.5	0	33	99.4
- Percent Increase in Component Sizes	45	-2	0	0	---	---
• 20% Decrease in Demand						
- For no Change in System Configuration	22	106	3.5	0	0	100.0
- For >99% Resource Availability	13	71	3.5	0	25	99.6
- Percent Decrease in Component Sizes	41	33	0	0	---	---

5.5.2 Effect of Random Demand Variation

Testing the robustness of the design to random demand fluctuation was conducted using a demand profile that varied randomly about the mean. A uniform random distribution with limits ± 20 percent around the mean value was used in generating the random hourly demand profiles. Exhibits 5-25 and 5-26 show a comparison of the daily kWh totals for the random and non-random demands for the Tunisian Village and Utirik.

Exhibit 5-27 shows a comparison of resource availability for each hybrid system for the random and non-random demand profiles. The designs are highly robust since there is no change in availability between the random and non-random demand profiles.

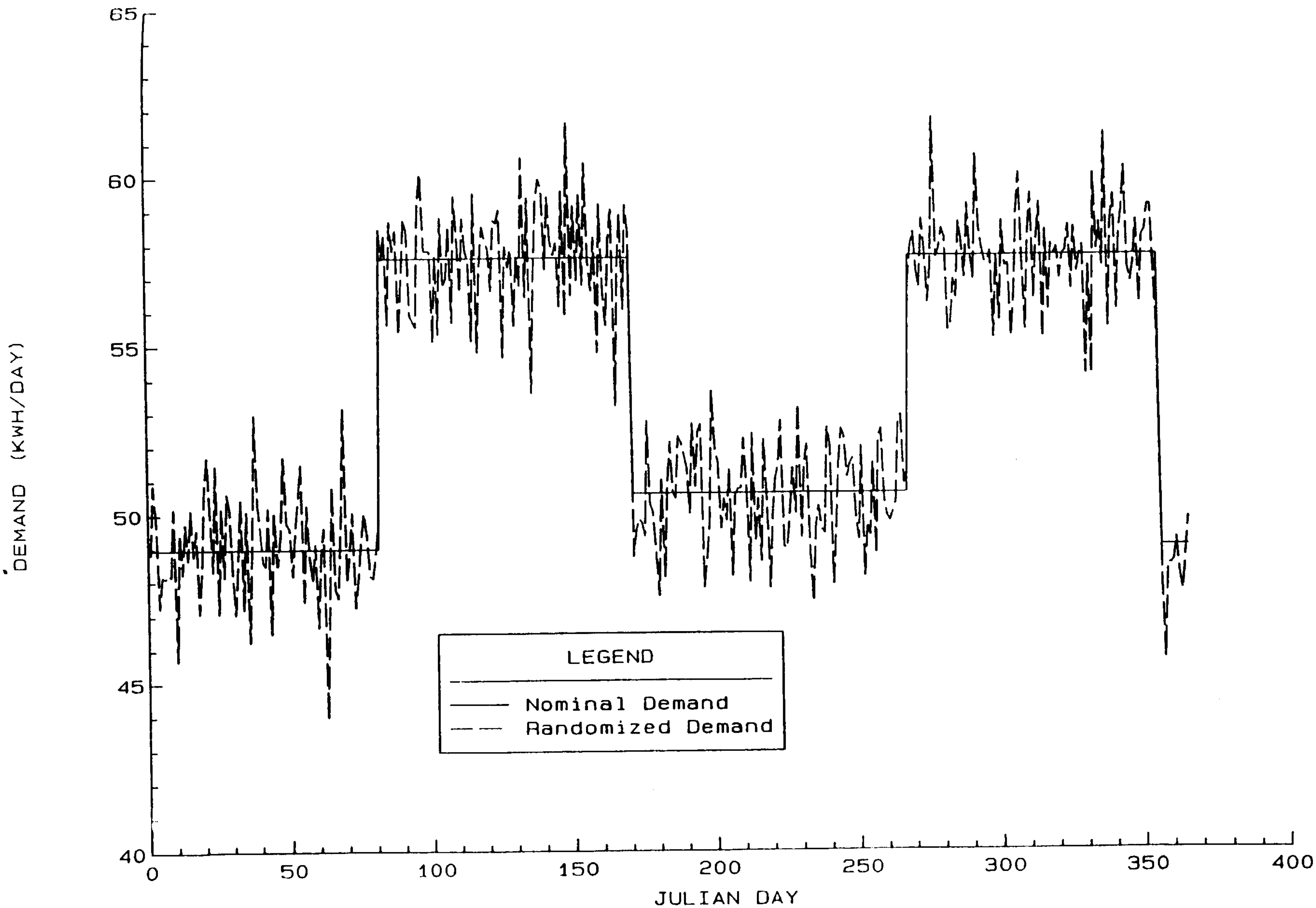

EXHIBIT 5-25: COMPARISON OF RANDOMIZED AND NOMINAL DEMAND FOR TUNISIAN VILLAGE

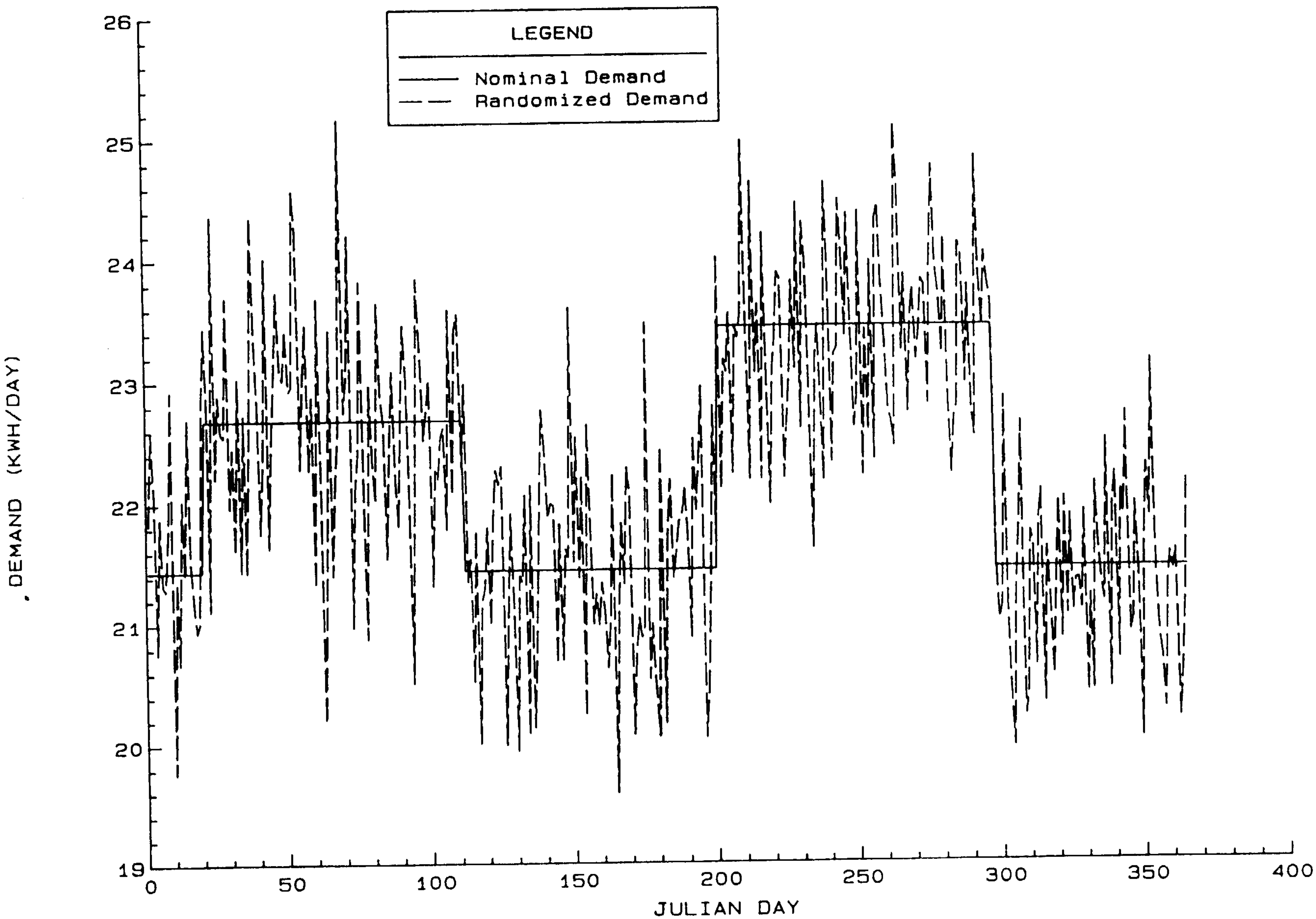

EXHIBIT 5-26: COMPARISON OF RANDOMIZED AND NOMINAL DEMAND FOR UTIRIK ISLAND

EXHIBIT 5-27

EFFECT ON ENERGY RESOURCE AVAILABILITY
OF RANDOM VARIATIONS IN DEMAND

SYSTEM	PERCENT RESOURCE AVAILABILITY	
	DETERMINISTIC DEMAND PROFILE	RANDOMIZED DEMAND PROFILE
<u>TUNISIAN VILLAGE</u>		
• PV/Wind	99.7	99.7
• PV/Diesel	99.8	99.9
• PV/Fuel Cell	100.0	100.0
<u>UTIRIK</u>		
• PV/Wind	99.6	99.6

6.0 DETAILED CONCEPTUAL DESIGN

This section discusses the detailed conceptual designs prepared for the Tunisian village and for Utirik Island. The discussions include the system descriptions, their operation, capital costs and maintenance requirements wherever possible, these designs use currently available state-of-the-art components, so that components and systems requiring additional R&D can be identified.

6.1 General Considerations in Design

In order to avoid duplication, this discussion is intended to cover equipment common to all four conceptual designs.

The sizing of the PV array, the battery and the alternate generator are based on the results of the computer simulation model analysis described in Section 5.0 of this report. Simulation model output has been adjusted to account for equipment reliability and component size availability. In each case, where the selected equipment varies from the computer calculations, slightly greater capacity has been selected, in order to ensure compliance with the calculations.

In each system, the inverter if required, is sized to the maximum load demand. Inverter selection then determines battery voltage, which must be compatible with the inverter D.C. input.

In order to maintain a constant D.C. supply, use of a TriSolar Incorporated Battery Controller is assumed. This device performs several functions as follows:

- Maintains the PV array at the peak power point.
- Down converts the variable D.C. voltages from the subarrays to a constant D.C. output voltage. This is done by means of a separate receptor for each subarray. The receptors, (down converters), then feed the master controller which maintains the peak power point. This arrangement also eliminates the need for blocking diodes in the subarray outputs, and, thus their inherent power loss.
- Maintains surveillance of battery condition by measuring energy-in and energy-out with an automatic reset of battery state-of-charge to 100 percent capacity when voltage reaches 2.4V per cell.
- Helps operate an external device, such as a contactor, to disconnect the battery when it nears the damaging discharge point, and reconnect it when recharged to a pre-determined level.

- o Allows excess energy to be dissipated with only a slight (3°C) increase in temperature of the PV array when excess energy is available from the array and the battery fully charged.

It would be desirable to design the various PV arrays around a typical subarray, allowing the same DC voltage to be applied to all systems. Coincidentally, the load requirement for the Utirik system is 120V D.C.; the same as the nominal input voltage for the inverter used at the Tunisian location. Thus, the difference among arrays for the various systems is only in the number of subarrays required to provide the desired peak wattage. Therefore, as discussed in Section 5.0, the PV array consists of a number of branch circuits (subarrays), each with 13 modules connected in series (See Exhibit 6-1).

Peak wattage of the basic 12 module subarray is 449Wp, of the 13 module subarray 487Wp and of a 14 module subarray 524Wp. Since the basic circuitry of the battery controller is rated 500W maximum, (one such circuit is required for each subarray), it is not prudent to go beyond the 13 module arrangement.

Connections within the PV array have been the subject of considerable study. "Cross-strapping" is sometimes provided as a means of increasing the probability of maintaining full output over long periods of time.

In these conceptual designs, cross-strapping is omitted, the cross connections required between modules of different subarrays cause the subarrays to disappear as individual units. Cross-strapping also makes trouble shooting very difficult. Since with so many alternate current paths, detection of a faulted module requires the individual testing of each. However, without the cross connections, areas of the array can be tested and the fault isolated in a fraction of the time it might otherwise take.

The many available current paths provided by cross-strapping will tend to maintain near full output of the array despite the possible failure of modules within it. The discussion of redundancy within the individual subarrays contained in Section 5.3.1, is based upon the omission of cross-strapping and its replacement by the use of a by-pass diode paralleling each module. The expected availability of 92.7% of design peak power output after 20 years under this concept compares favorably with 94.3% availability under the cross-strapped concept. The noted ease of trouble shooting far offsets the 1.6% possible increase in peak power output.

Also the basic 12-module subarray delivers 187VDC at 48°C and the addition of the 13th module increases this to 203VDC. This variation is accommodated by the down converters to maintain an acceptable DC voltage range for inverter supply and battery charging.

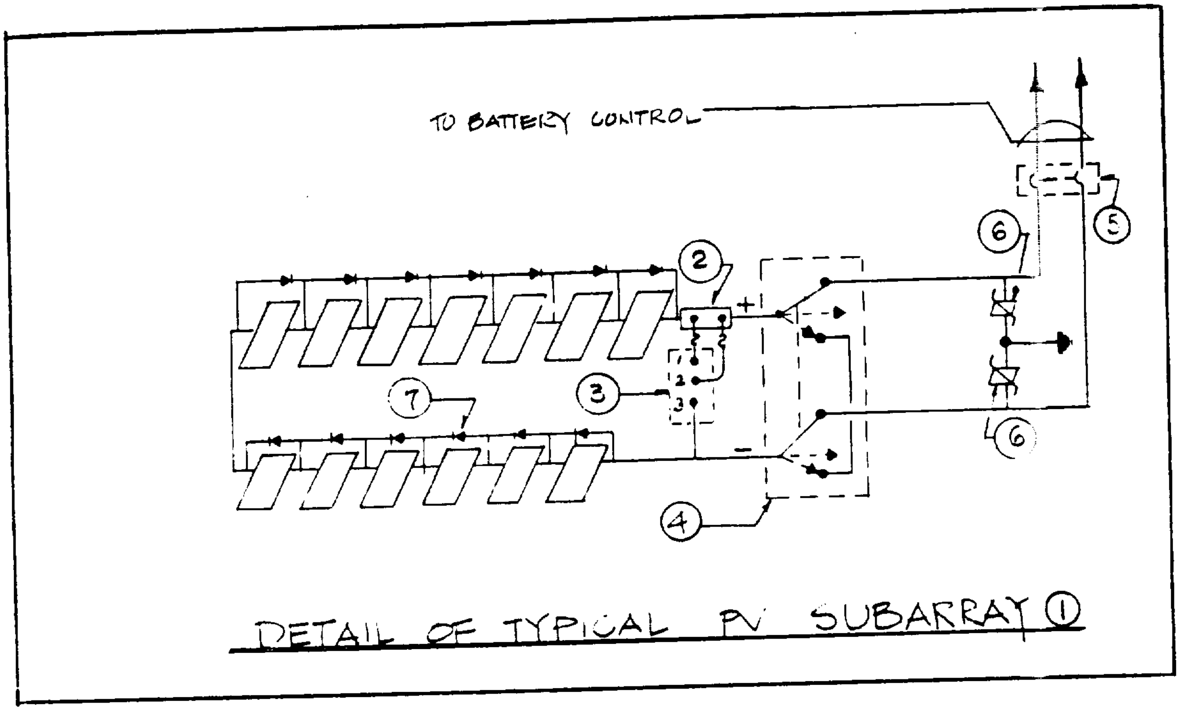

EXHIBIT 6-1

DETAILS OF PV SUBARRAY FOR THE TUNISIAN VILLAGE

Legend:

1. Subarray - 13, 36 cell modules each developing 15.6V and 2.4Ap for a total output of 203V, 487Wp.

2. Shunt - For measurement of current.

3. Fused Test Point - 1-2 measure current (short circuit and operating) 1-3 measure voltage (open circuit and operating).

4. Output Switch - 2P weatherproof double throw, three position, switch rated 30A, 250VDC.

5. Circuit Breaker - 2P, 5A, 250VDC for protection and isolation of subarray. Located in equipment

6. Varistor - Shunts voltage surge ground for lightning protection. For best protection, provide two subarray, two more in equipment for each subarray.

7. Bypass Diode - Shunts out failed module. Typical of 13. Rating $50V_{RRM}$, 95°C operating.

With this arrangement, actual voltage to the inverter will range from 114VDC, (1.9V/cell), to 144VDC, (2.4V/cell). The former is the maximum allowable battery discharge point, the latter the maximum charge point. The selected inverter will accept this variation while still maintaining the desired output of 220VAC, 50Hz.

The positioning of the PV array is of great importance. A south orientation (for northern latitudes) is essential. A fixed angle of tilt equal to the latitude of the site is assumed for the conceptual designs. This gives maximum power at the two annual equinoxes, spring and fall. Since the earth precesses approximately 23° each way at the summer and winter solstices, power availability decreases to a minimum of about 90 percent of that available at the equinoxes.[1] If necessary, in order to maximize array output, adjustable struts are used so that the modules can be seasonally set at an optimal angle of inclination (See Exhibits 6-2 and 6-3).

The inverter selected for the Tunisian systems is Best Energy Systems, Inc., Model M120-6000. This unit is available with a 50Hz, 220V output. It is self-commutated, and, thus applicable to a stand-alone system. According to the manufacturer, it produces a modified square wave with a maximum distortion of 20% from a pure sine wave. Such a wave is considered satisfactory for the operation of incandescent or discharge lighting and small motors. In addition, this inverter will accept momentary overloads of 25% which would accommodate the starting of small motors.

Recently this type of inverter has become available from other manufacturers (e.g. DECC Division of Helionetics).

The battery in each system must be capable of deep discharge and be rugged enough to offer a long life. Of the several types of batteries available,the lead (antimony) - acid and the lead (calcium) - acid are universally preferred for the type of service contemplated in these designs.

The lead calcium battery has an advantage, because charging does not require as high a voltage as the lead antimony type, thus reducing gasification and water loss. However, these batteries, particularly the deep discharge type, are much more expensive than the lead antimony type. Therefore, these conceptual designs have assumed the use of a heavy duty lead antimony battery manufactured by the Surrette Storage Battery Company. The batteries selected for these designs are rated by the manufacturer for a 15 to 20 year life.

The battery array consists of subarrays of 10, 12V batteries in series. The requisite number of battery subarrays are connected in parallel to provide the necessary battery storage capacity.

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1 Monegon, Ltd., "Designing Small Photovoltaic Power Systems," Monegon Publication No. M111.

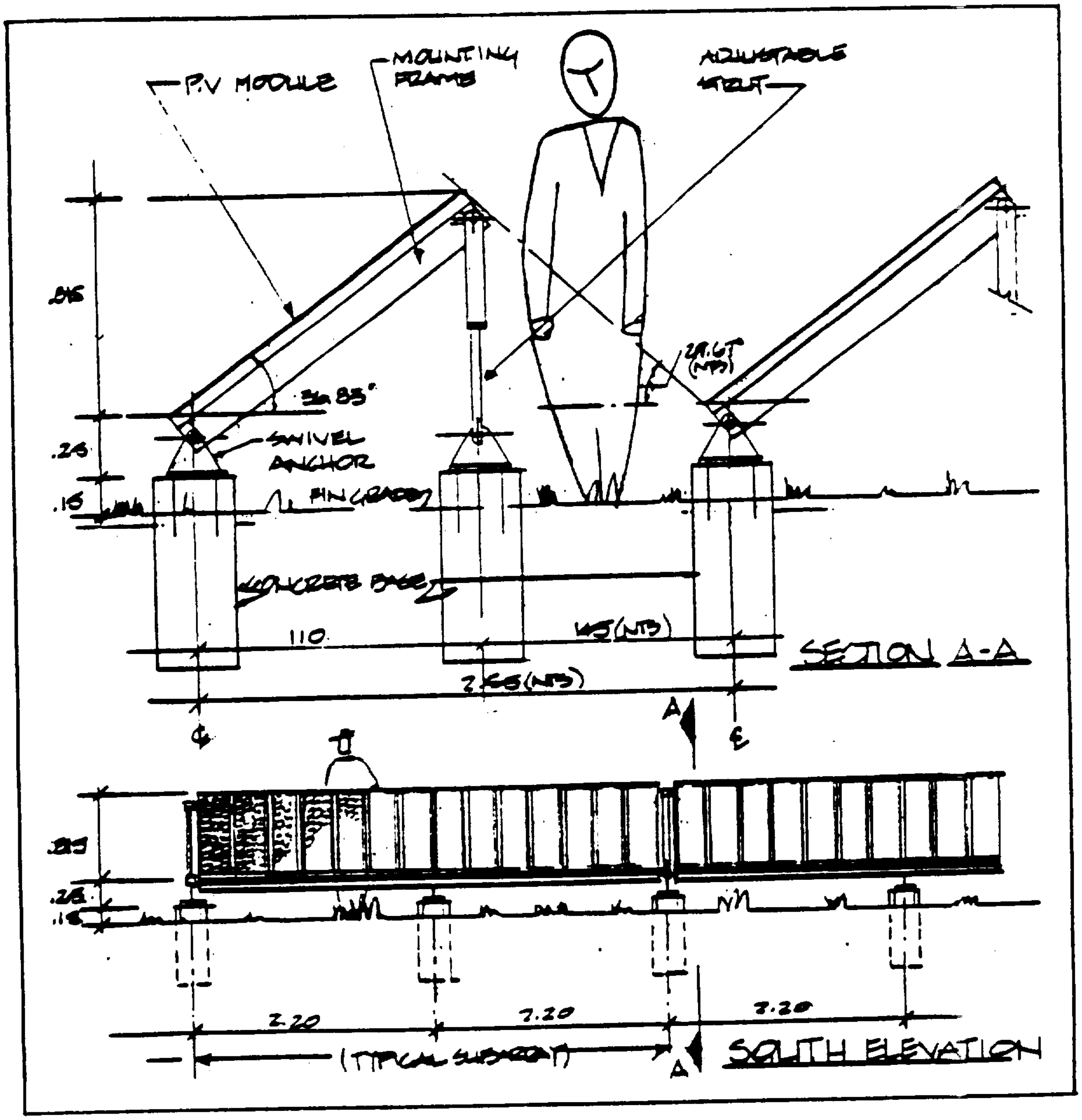

EXHIBIT 6-2

PV ARRAY INSTALLATION FOR THE TUNISIAN VILLAGE

In order to make the lead antimony battery comparable in operation to the lead calcium type, "Hydrocaps" should be used on each cell rather than regular caps. These caps contain a catalyst which causes the hydrogen and oxygen emitted from the electrolyte during charging to recombine into water and drip back into the cell chamber. This action reduces the possibility of explosion due to free hydrogen in the air and decreases water loss significantly.

In a further comparison between the lead antimony and lead calcium batteries, it is recognized that the lead calcium type has an extremely low self discharge rate of about 1% to 2% of battery capacity per month. The Surrette lead antimony plates are rather unique in their field. They are of heavier construction and, for the battery selected, the manufacturer states that self discharge rate is 4% per month.

In addition, lead antimony batteries are less expensive than lead calcium. One lead calcium battery manufacturer quoted prices ranging from $329 per 6 volt battery (225 Ah at 8 hour rate) for small quantities to $230 each for 160 or more. Surrette has quoted $205 per 12 volt battery (221 Ah at 20 hour rate), including Hydro--caps, in any quantity. For the eight 120 volt (60 cell) strings required for the PV/wind system at the Tunisian village, the lead calcium batteries would cost $36,800 versus $16,400 for the lead antimony batteries based on the Surrette quote. These quotations are for dry-charged units and do not include electrolyte, jumper cables, racks, etc. Cost of these items except for cables are considered approximately equal. However, jumper cable would be more expensive with the 6 volt battery compared to a 12 volt battery.

In the PV/diesel and PV/fuel cell systems a time switch is used. This is a standard time clock with necessary electrical contacts programmed to open and close at specific times. The clock is also equipped with a cam which makes one complete revolution per year, and continually resets one set of contacts to "follow the sun" to close at sunset and open at sunrise. This is known as an "astronomic dial" and for accuracy, the cam should be selected for the approximate latitude. Most manufacturers provide an adjustment of up to 40 minutes before and after sunset, (or sunrise), so that one cam can serve a range of latitudes. In the conceptual designs the time switch is set to activate just after sunrise and just before dusk, when insolation is approximately 15% of peak.

Grounding is provided for two general areas, the supporting framework for the array and the system ground. The latter also serves as a ground point for lightning protection for the wind generator tower where applicable.

Ground fault protection is provided for the array as a whole rather than attempting such protection for each sub-array individually. This is because experience has shown that within the modules

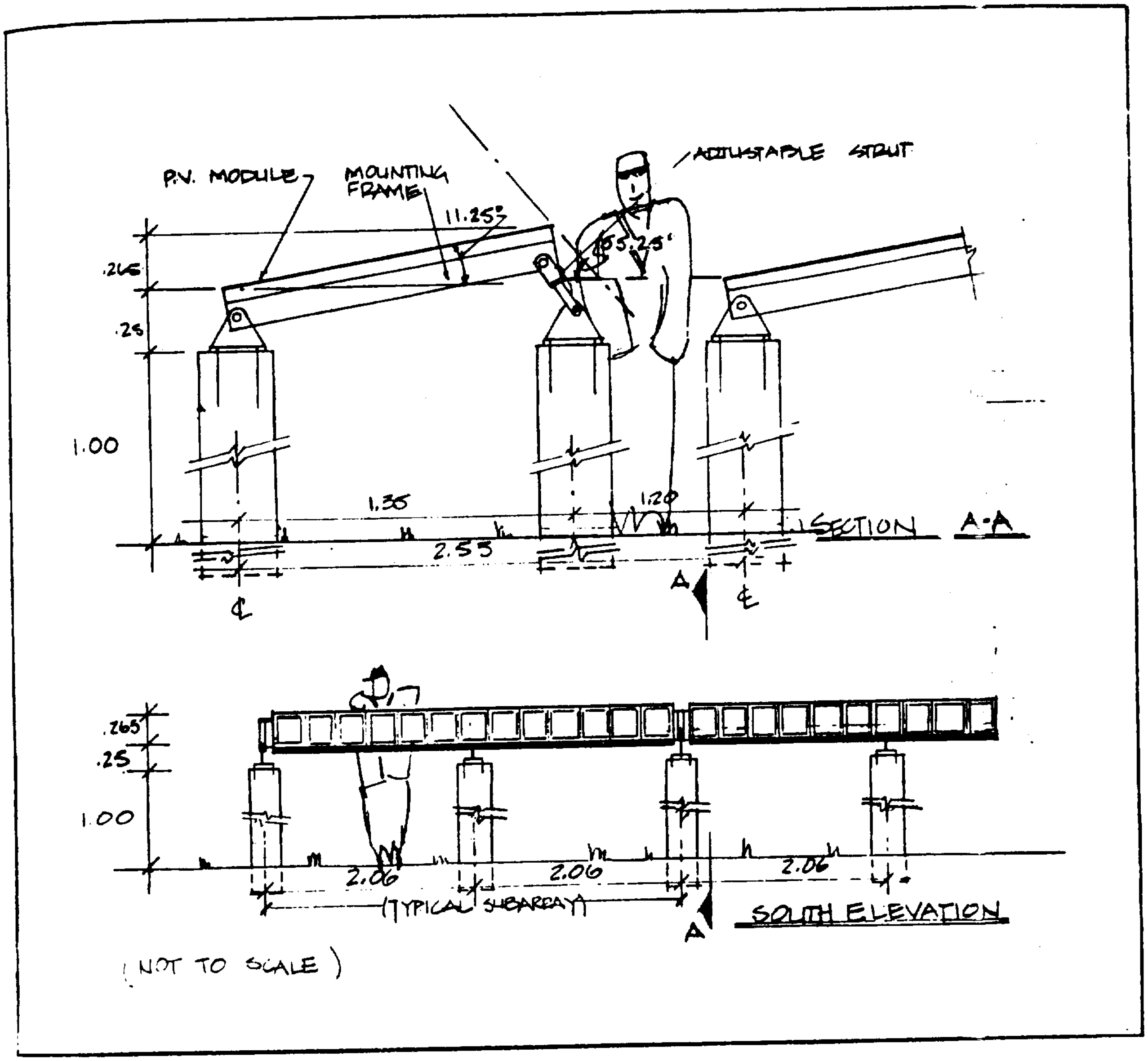

EXHIBIT 6-3

PV ARRAY LAYOUT FOR UTIRIK ISLAND

of the array, ground faults are very rare. Although ground fault protection on this overall basis means shutting down the entire system rather than a small, affected portion, the risk is considered small due to the rarity of such events.

As noted above, the grounding of the array framework provides a direct path for possible naturally produced static surges. There is little, if any protection available for a direct lightning strike.

The subarrays are also individually protected against surge or impulse by the provision of "Varistors", solid state devices which act to instantly drain to ground any overvoltage that may appear in the circuitry of the subarrays. The Varistors are chosen because after such action they are self-healing and immediately return to the normal operating mode.

Other devices are the same as utilized in all electrical systems such as appropriately placed and sized circuit breakers, fused switches, etc.

6.2 PV/Wind System, for the Tunisian Village

6.2.1 Description of System Elements

Exhibit 6-4, shows a single-line diagram of the system and provides a list of the basic components.

This system is designed to provide approximately 5.4kW of power at approximately 114 to 144 volts DC to a 5.0kW inverter having a 220V, 50Hz, single phase output.

The PV array consists of 14 of the "standard" subarrays, each initially providing nearly 203VDC from 13 modules in series. The array is designed to develop 6.8kWp, sufficient, with the wind generator to fully serve the load as well as charge the battery.

The array/battery controller, Cp, also includes a battery sensing section measuring coulombs of energy of charge and coulombs of energy of discharge, thus sensing at all times the state of charge of the battery. This section of the controller also operates the contactor (Item F in Exhibit 6-4) to disconnect the battery when it reaches its maximum discharge point. This of course presumes that neither the PV array nor the wind generator is producing sufficient power to maintain the system without further battery discharge.

The array/battery controller, Cp, also includes circuitry to restrict charging of the battery (by the PV array and/or the wind generator) to periods when excess energy is available (i.e. when load demand is met). When there is inadequate power and contactor F is open, and if sufficient power subsequently becomes available from the PV array and/or the wind generator, this circuitry allows the contactor to again close to serve the load. This prevents any possibility of "hunting", that is, intermittent operation of the

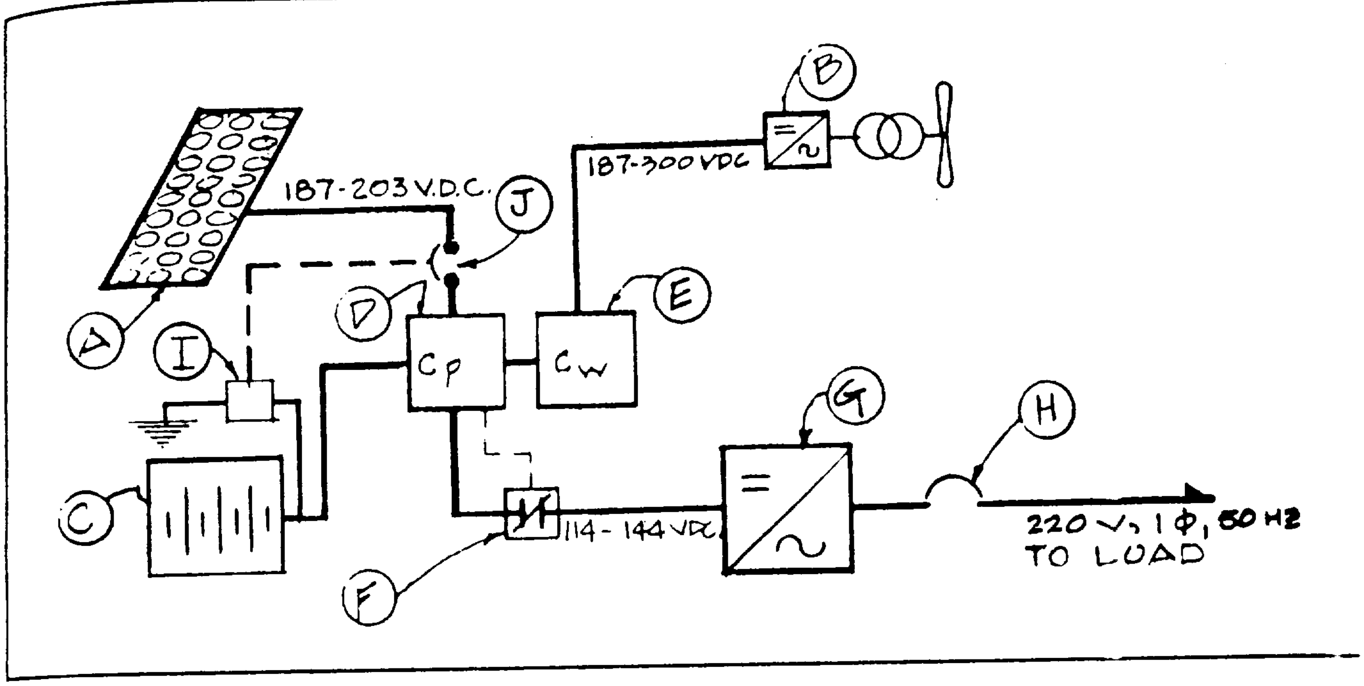

EXHIBIT 6-4

SINGLE LINE DIAGRAM OF THE TUNISIAN VILLAGE PV/WIND HYBRID

Legend:

Basic System Components

A. PB Array: 14 subarrays - see detail of typical subarray, Exhibit 6-1.

B. Wind Generator: Wind generator with 7m blade, permanent magnet rotor and rectifie 10kW rating to develop 200 to 300VDC with 28A load and wind speeds from 3m/s to 1

C. Battery: Lead antimony type, 120VDC nominal. See Exhibit 6-7 for details.

D. Array/Battery Controller Cp: TriSolar type MPCB-P14 maintains battery charging/ inverter input voltage, tracks array at peak power point, maintains continuous log of battery charge, disconnects battery at 80% discharge point, reconnects battery when charging energy is available.

E. Wind Generator Controller Cw: TriSolar type MPC-P10. Down converts variable DC voltage from wind generator to VDC required by master controller portion of Cp.

F. Battery Contactor: Rated 250VAC, 50A, remote control by battery controller, normally closed contact.

G. Inverter: Receives indicated input voltage range. Output 220V. 50Hz to maximum 5.0kW load.

H. Output Breaker: Rated 250VAC, 30Z trip for protection of inverter in case of fau

I. Ground Fault Protector: From negative side of battery to ground. If ground faul is detected, trips array breaker.

J. Array Breaker: 50A, 250VDC, 2P, with shunt trip.

contactor as a result of partial recharging of the battery. In the interim period, before power builds sufficiently to serve the load, available power is used for battery charging.

The wind generator controller, Cw, (Item E in Exhibit 6-4), accepts a wide range of voltage output from the wind generator and down converts it to the same voltage as received by the battery controller section of Item D. In this manner varying D.C. voltages from both the PV array and the wind generator are made compatible, and both serve the battery and the system in a controlled manner.

The wind generator (Item B in Exhibit 6-4) is rated at 10 kW, at a wind speed of 12 mps. It consists of a housing containing a permanent magnet alternator driven by a three bladed propeller approximately 7m in diameter. A rectifier is provided to serve the system with direct current. Cut-in wind speed is approximately 3 mps and the device will generate full power at about 12 mps. Beyond this wind speed there is a controlling governor to allow a maximum rotational speed in the area of 200 to 250 rpm. Furling wind speed is about 16 mps.

It is noted that the output voltage of a wind generator decreases with increasing load and increases with increasing wind speed. Neither relationship is linear and varies with different manufacturers. For this reason, this study assumes the use of a wind generator voltage controller of established compatibility with the battery controller rather than the wind generator manufacturer's voltage regulator.

A 20 m tower has been selected. This should be high enough to avoid wind disturbance from nearby buildings and trees. It also provides a minimum height above ground of approximately 15 meters for the rotating blades. This is considered sufficient to avoid possible hazards.

The battery contactor (Item F in Exhibit 6-4) is only for battery protection. As noted above, it is opened by the battery controller only when necessary to avoid damaging discharge.

The inverter is of the self-commutated type as described in Section 6.1 of this report. The output circuit breaker is used for disconnecting the system from the load in case of an overload or short circuit in the power distribution system or load devices.

Exhibits 6-5 through 6-7 show additional details of the PV/wind system design.

6.2.2 Operation

This system is designed for automatic operation. At any time during the day or night when there is sufficient wind to allow the wind generator to produce more than about 185 volts, it begins to provide power to the battery controller.

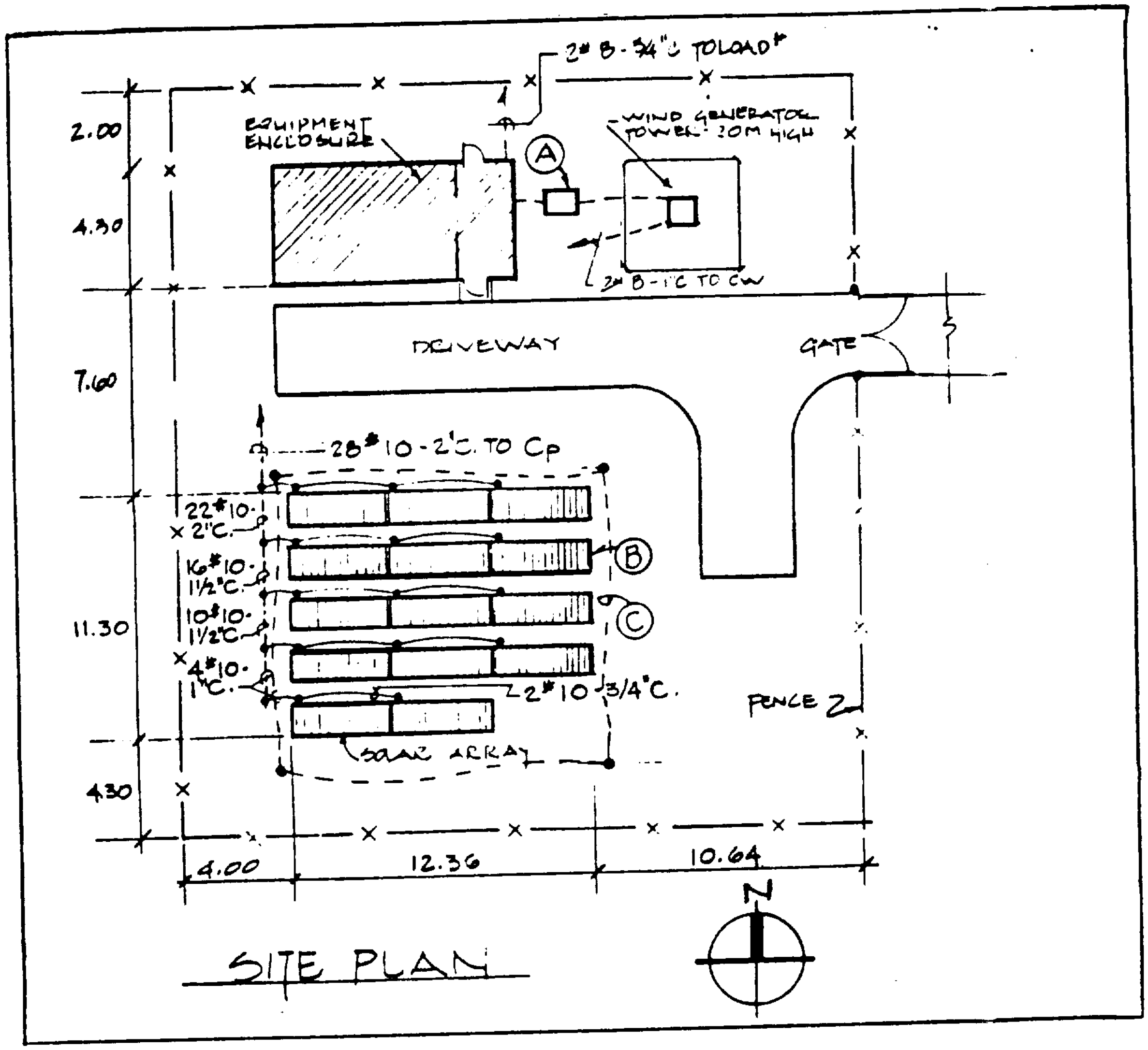

EXHIBIT 6-5

SITE PLAN FOR THE TUNISIAN VILLAGE PV/WIND HYBRID

Legend:

A. Plate or coil ground to provide maximum 25 ohm ground resistance. Indicated connections are for tower lightning protection and system ground.

B. PV array consisting of 14 subarrays, (see Exhibit 6-1). Peak watts: 6818. Each subarray separately circuited to the array/battery controller.

C. Ground loop with ground rods for grounding array framework. Maximum ground resistance 25 ohms.

Notes:

1. Dimensions shown are in meters.

2. Conductor size may vary depending on actual length to control voltage drop and I^2R loss.

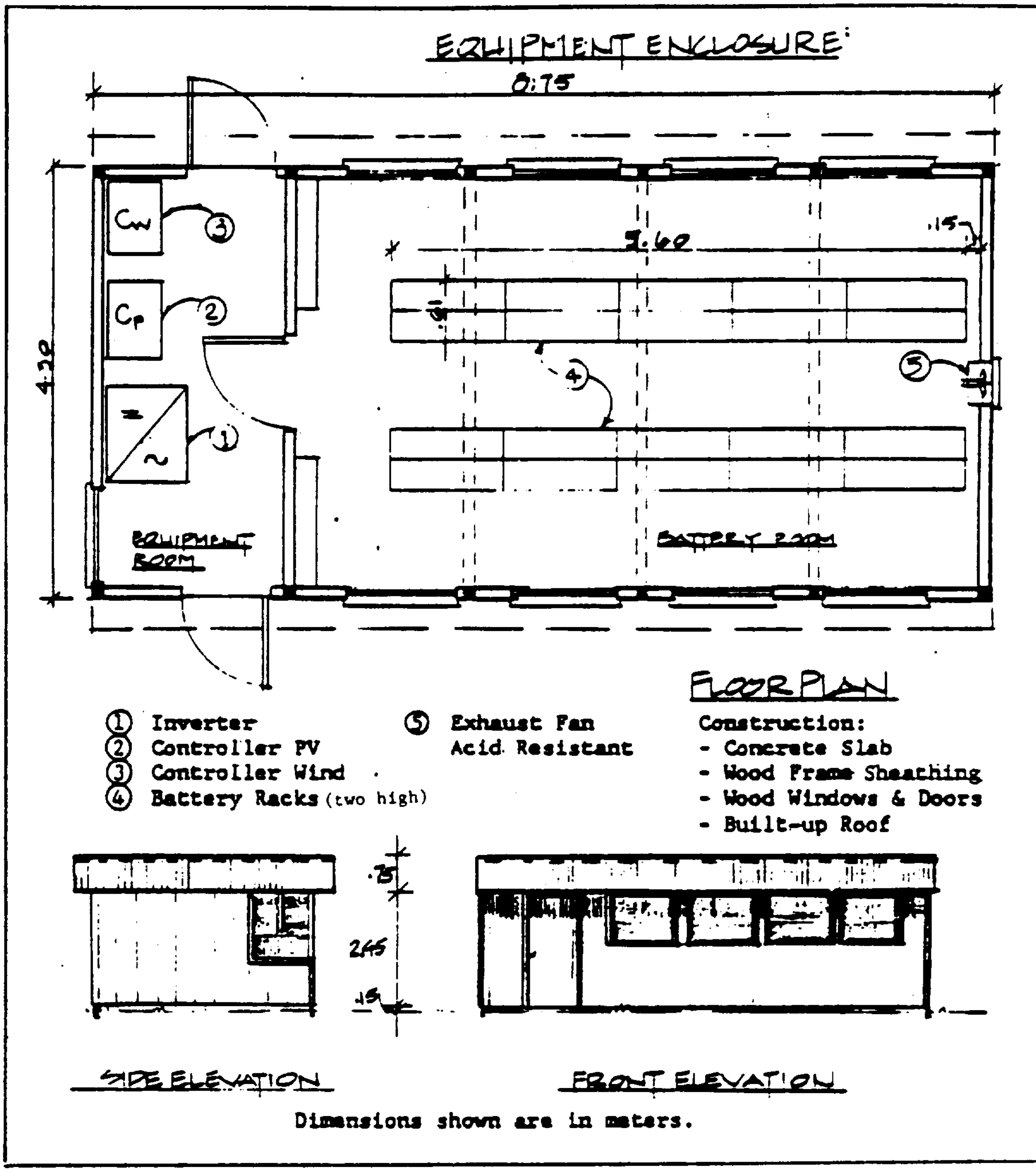

EXHIBIT 6-6

EQUIPMENT ENCLOSURE FOR THE TUNISIAN VILLAGE PV/WIND HYBRID

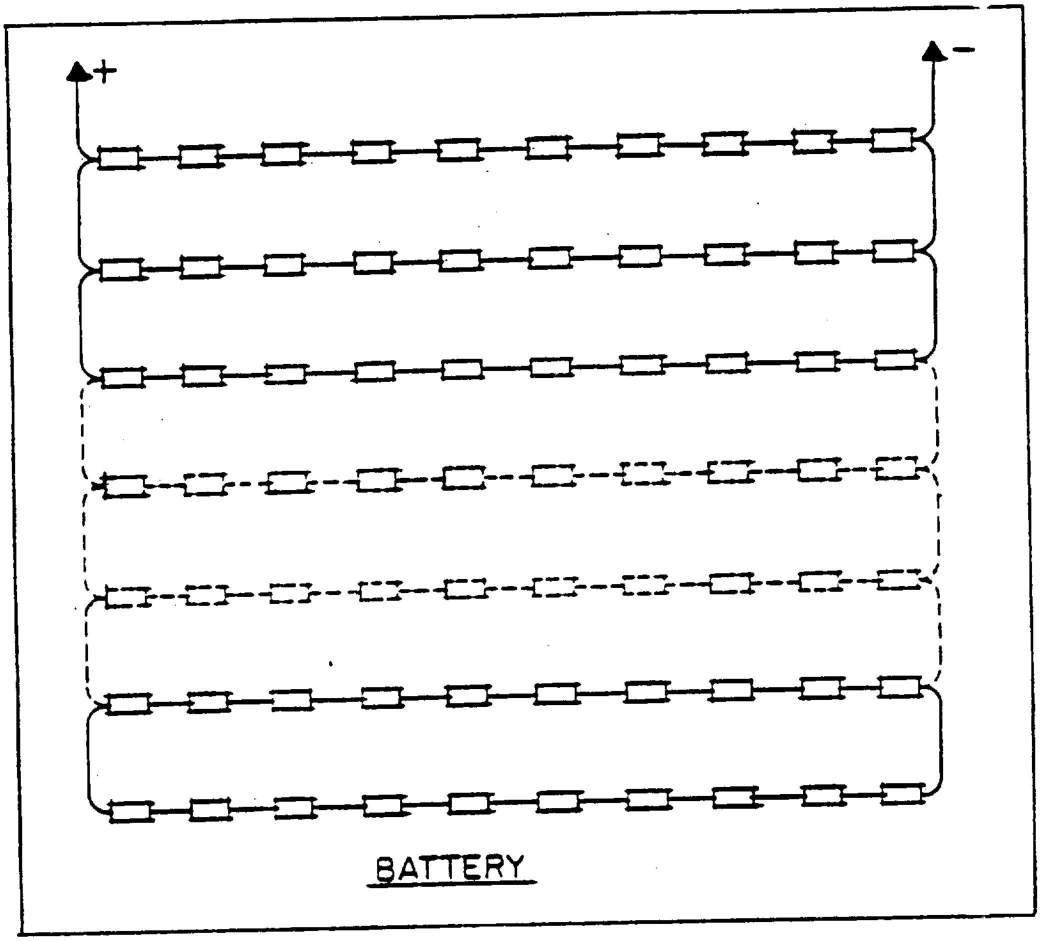

EXHIBIT 6-7

BATTERY LAYOUT FOR THE TUNISIAN VILLAGE PV/WIND HYBRID

Legend:

No. of Batteries in a String: 10
No. of Strings: 8
AH/String: 221 (20 hour rate)
Total AH: 1,768
Total kWh: 212.16

Manufacturer: Surrette
Cat. No. 427EH
Size: 221 AH (20 hr. rate)
2 volts/cell
12 volt/battery
Size: 20-1/16 long, 11" wide
9-3/4 high
Wet Weight: 165 pounds

When there is sufficient sunlight, the PV array also provides power. The two sources in parallel serve the battery controller which, in turn, charges the battery with energy in excess of that required by the inverter to carry the load.

When neither insolation nor wind is sufficient, the battery provides necessary energy at 120V (nominal) to power the load through the inverter until the battery reaches a depth of discharge of 80%, (20% of charge remaining). At this point, the battery controller opens the contactor utilizing the remaining battery energy and holds it open until either the wind generator or the PV array, or both, have restarted to provide sufficient energy to operate the inverter and serve the load. The battery controller then allows the contactor to reclose. In the meantime energy from the array and/or the wind generator goes to recharging the battery.[1]

Since the controllers perform the function of reverse power protection, it is not necessary to provide blocking diodes between either the wind generator or the PV array and their respective controllers.

6.3 PV/Diesel System, for the Tunisian Village

6.3.1 Description of System Elements

Exhibit 6-8, shows a single-line diagram of the system and provides a list of its basic components.

The system is designed to provide approximately 5.4 kW at 114 to 144VDC to a 5.0kW inverter which, in turn, will provide 220V, 50Hz, single phase power to the village.

The PV array consists of 25 of the "standard" subarrays, each initially providing nearly 203VDC from 13 modules in series. The array is designed to develop 12.2kWp, sufficient, with backup from the diesel-electric set, to fully serve the load as well as maintain the battery charge.

The array/battery controller also includes a battery sensing portion which maintains a continuous log of battery status by measuring input (charging), coulombs of energy, and output (discharging) coulombs. This section also has the capability of operating the contactor, (Item F in Exhibit 6-8) and starting and stopping the diesel-electric set through its starting panel as discussed in Section 6.3.2 —Operation. It also prevents battery charging until the PV array is producing power in excess of that required by load demand.

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1 Final design for this sequence may vary since it may be found desirable to serve a partial load or to adapt to final selection of equipment.

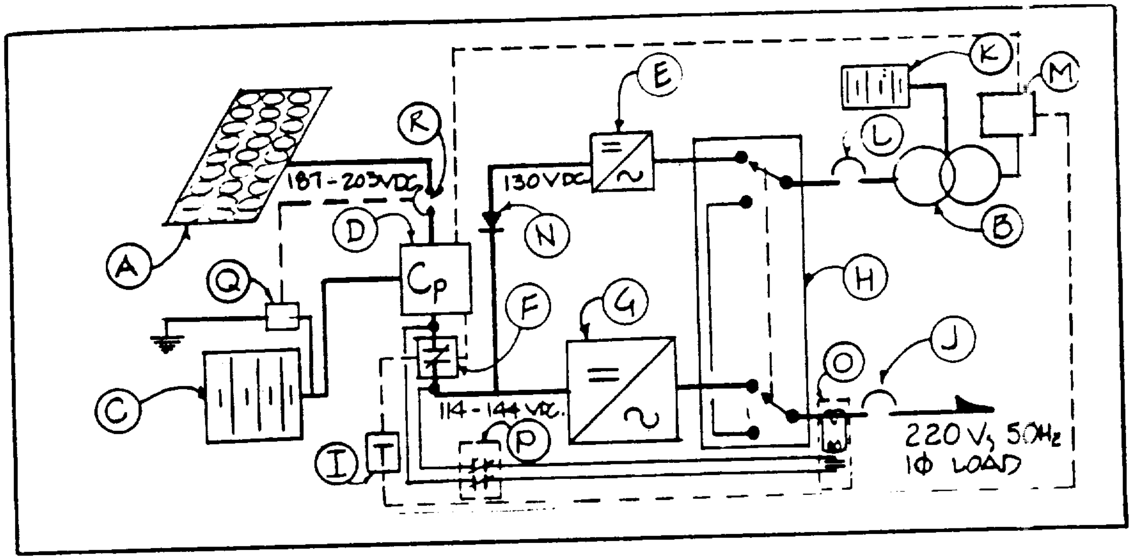


EXHIBIT 6-8

SINGLE LINE DIAGRAM OF THE TUNISIAN VILLAGE PV/DIESEL HYBRID

Legend:

A. PV Array: 25 subarrays - see detail of typical subarray Exhibit 6-1.

B. Diesel-Electric Set: 4kW Onan Model 4.ODADB-3E, air cooled modified for 220V, 50Hz with starting panel and battery charger.

C. Battery: Lead antimony type, 120VDC nominal, see Exhibit 6-11 for details.

D. Battery Controller: TriSolar Model MPCB-P25 maintains battery charging and suppl to inverter. Maintains continuous log of battery charge and opens contactor F a 80% discharge point. Reconnects when charging energy available.

E. Rectifier/Regulator: Allowing diesel-electric to serve the inverter.

F. Contactor: 250VDC, 50A, normally closed, remote control by Battery Controller D and Time Switch I.

G. Inverter: Output 220V, 50Hz to maximum 5.0kW load.

H. Transfer Switch: 30A, 250V, allows Diesel Electric Set to back-up PV array or serve load directly, manual operation.

I. Time Switch: With astronomic dial to start diesel in the evening and switch loa Also stops diesel in morning and switches load back to array. Also opens contactor P for daytime operation.

J. Output Breaker: 250VAC, 30A trip for protection against downstream fault.

K. Diesel Starting Battery

L. Diesel-Electric Output Breaker

M. Diesel Starting Panel

N. Blocking Diode

O. Current Transformer and Relay

P. Bypass Contactor

Q. Ground fault protector from negative side of battery to ground. If ground faul is detected, trips array breaker.

R. Array Breaker: 50A, 250VDC, 2P with shunt trip.

The alternate generator in this system is a 4kW diesel-electric set providing 220V, 50Hz, single phase AC power. For simplicity, an air cooled unit has been selected. It is equipped for automatic starting utilizing its own small, 12V battery. It is also furnished with an alternator/rectifier for recharging this battery after starting.

In order to avoid excessive carbon buildup in the cylinders and the resulting requirement for a major overhaul, the output of the generator is equipped with a current transformer and associated relay. When the current flowing from the diesel-electric set falls below nine amperes, representing 2,000W at 220V, or 50% load, the relay drops out and causes the diesel engine to stop.

The diesel-electric set is provided with a rectifier/regulator to normally serve the load through the inverter. This allows it to provide backup for the battery during the day. The diesel-electric set is not used to charge the battery, because of the economy of the respective operating modes as reported in Section 4.2.2. A blocking diode is provided to prevent reverse current from flowing into the rectifier.

At full load, the 4kW diesel-electric set burns approximately 0.5 gallons of No. 2 diesel fuel per hour. On this basis, a 275 gallon fuel storage tank is provided giving a maximum operating time, when full, of 550 hours or about two months, depending upon the time of year and weather. A larger storage tank may be advisable depending on supply availability.

Exhibits 6-9 through 6-11 provide additional detail on the PV/diesel design.

6.3.2 Operation

The PV/diesel is designed for automatic operation.

Modes of Operation

1. Daylight hours

   A. With sufficient insolation the system operates entirely from the array which charges the battery and serves the load through the inverter.

   B. When insolation is reduced to a point where the array cannot fully serve the load through the inverter, the battery automatically commences to discharge and make up the difference.

   C. When the battery discharges 80% (expected to be rare) contactor F (Exhibit 6-8) is opened by the array/battery controller Cp, which at the same time sends a signal to

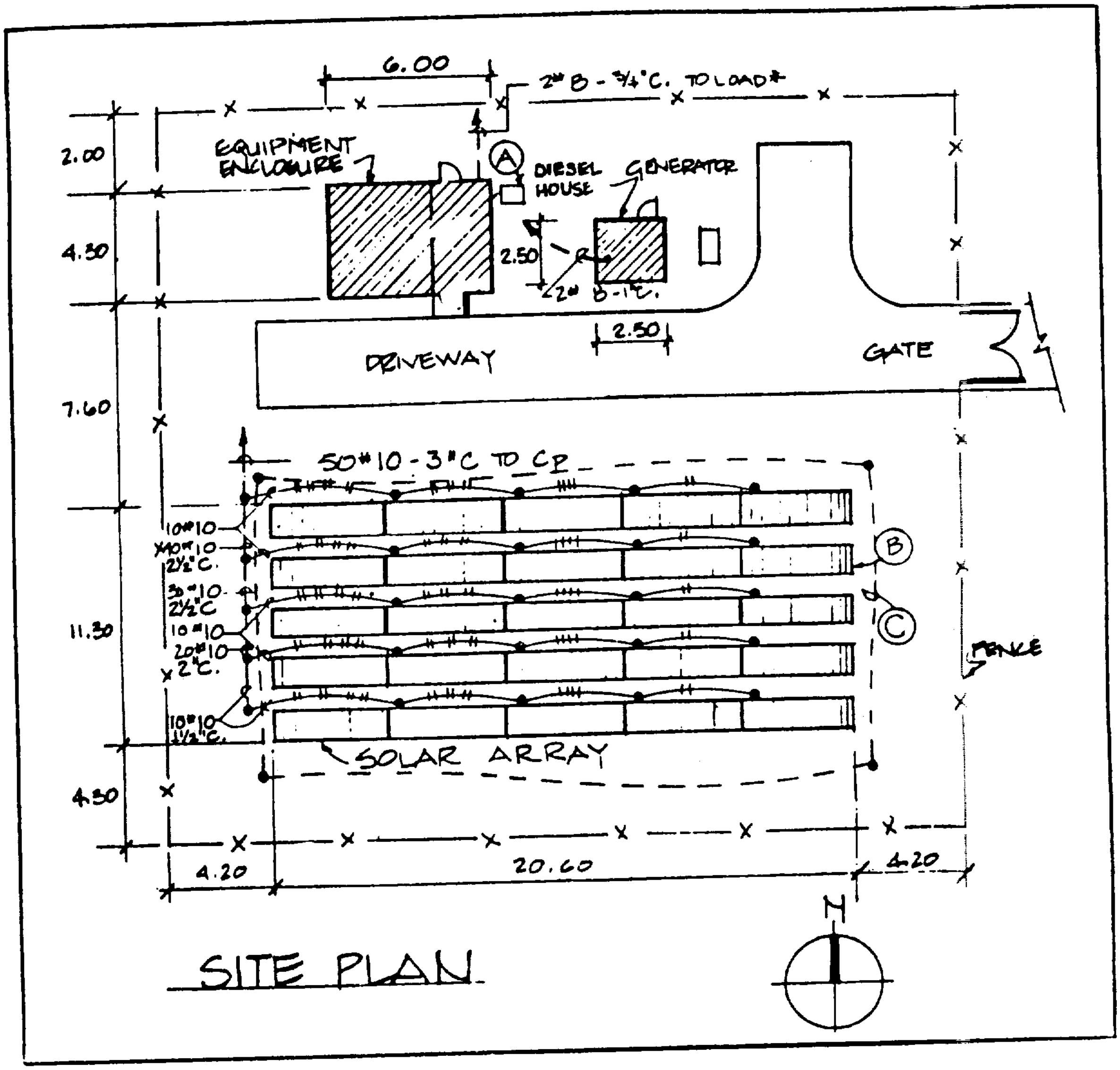


EXHIBIT 6-9

SITE PLAN FOR THE TUNISIAN VILLAGE PV/DIESEL HYBRID

Legend:

A. Plate or coil ground to provide maximum 25 ohm ground resistance for system ground.

B. PV array consisting of 25 subarrays, (see Exhibit 6-5). Peak watts 12,175. Each subarray separately circuited to the array/battery controlle

C. Ground loop with ground rods, maximum resistance 25 ohms. Connect to module support framework.

Notes:

1. Dimensions are in meters.

2. Conductor sizes may require change to minimize voltage drop and I^2R loss when actual lengths are determined.

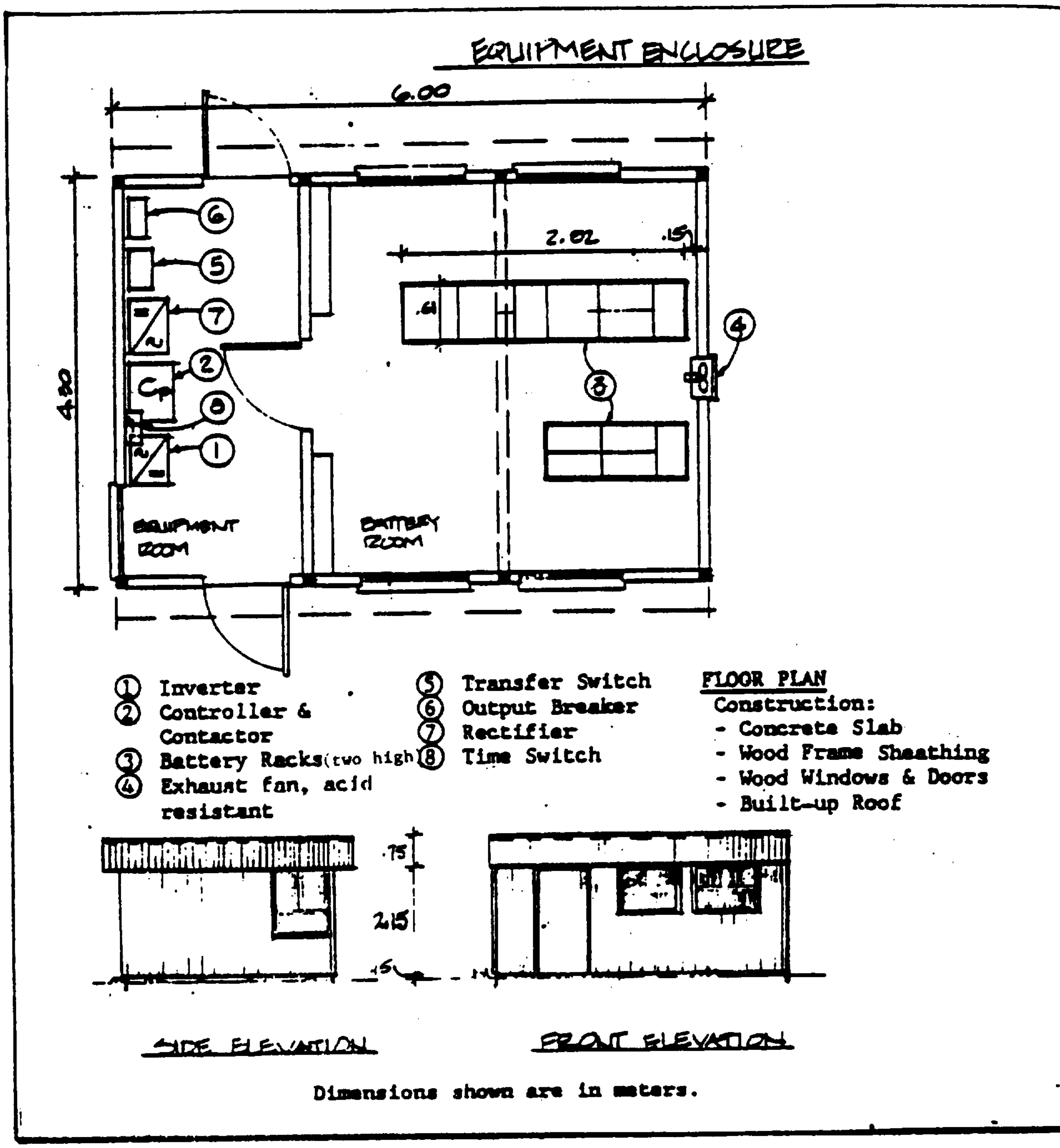


EXHIBIT 6-10

EQUIPMENT ENCLOSURE FOR THE TUNISIAN VILLAGE PV/DIESEL HYBRID

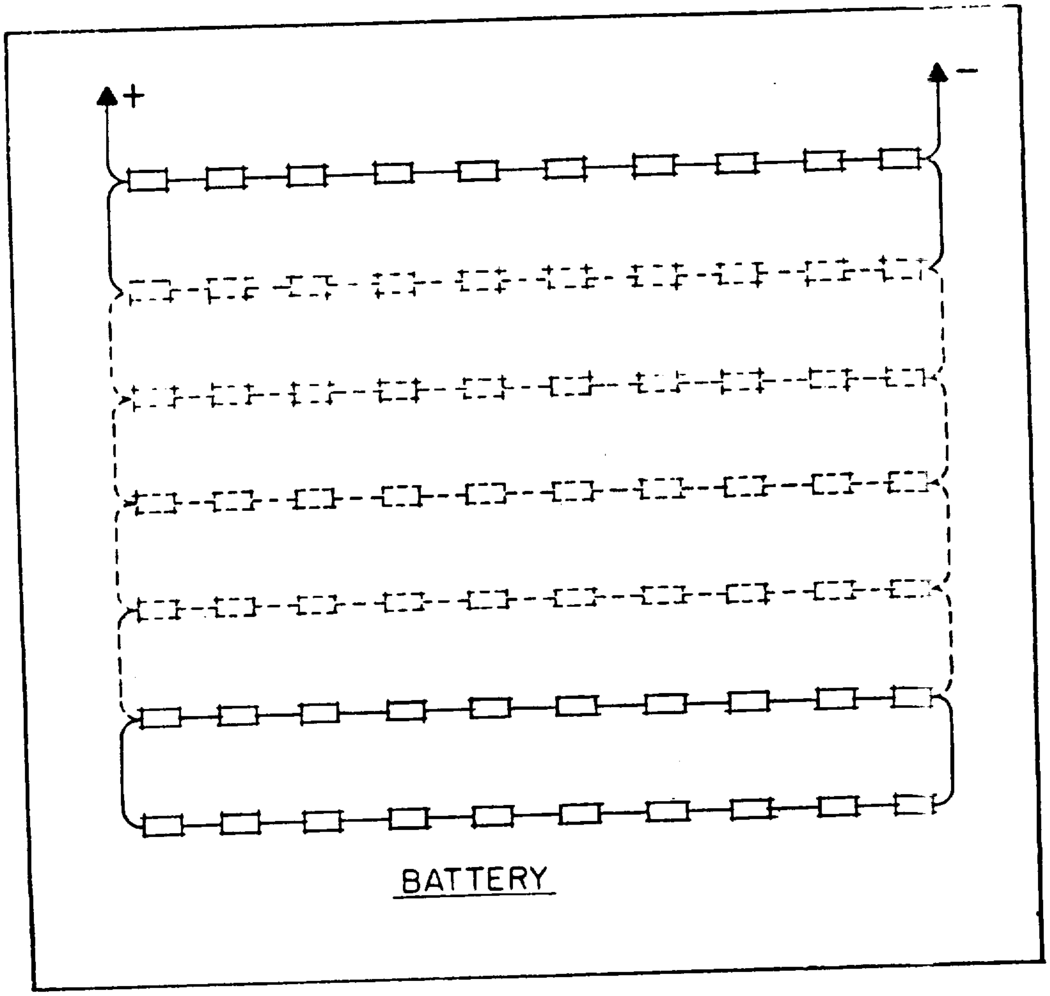


EXHIBIT 6-11

BATTERY LAYOUT FOR THE TUNISIAN VILLAGE PV/DIESEL HYBRID

Legend:

No. of Batteries in a String: 10
No. of Strings: 3
AH/String: 221 (20 hour rate)
Total AH: 663
Total kWh: 79.56

Manufacturer: Surrette
Cat. No. 427EH
Size: 221AH (20 hr. rat
2 volts/cell
12 volt/battery
Size: 20-1/16 long, 11" wid
9-3/4 high
Wet Weight: 165 pounds

the diesel-electric set to start and provide 120VDC to the inverter to continue serving the load. (Since the diesel-electric set has a capacity of 4kW which is reduced by the efficiency of the rectifier and the inverter to approximately 3kW output to the load, it may be necessary to shed some load in this case).

2. Nighttime hours

A. The time switch, (Item I in Exhibit 6-8) is set to start the diesel-electric set and open contactor F in the evening when insolation has fallen to approximately 15% of peak. The diesel-electric set serves the load through the inverter while remaining sunlight continues to charge the battery.

B. When the load on the diesel-electric set falls below 50% of its capacity, it is automatically stopped to avoid the carbon buildup which occurs in the cylinders under light loads. The current transformer portion of Item O (Exhibit 6-8) also senses the reduced load and closes its associated relay. This in turn bypasses contactor F and reconnects the battery which continues to serve the reduced load through the inverter. Under this mode, if the battery discharges to the point where it might be damaged the array/battery controller opens the bypass contactor P (contactor F is already open) and disconnects the battery. If the load increases to over 50% of the diesel-electric set capacity and remains at this level for a preset time, the set is again started and the relay in Item O opened to cut off the battery and return the load to the diesel-electric set as in Mode 2.A.

C. When sunrise comes and insolation increases to approximately 15% of peak, the time switch set for this time of day closes contactor F and opens contactor P, thus, resetting the system for normal daytime operation.

3. Emergency Operation

A. In case of inverter failure or other major breakdown in the DC portion of the system, it is possible to serve the load directly from the diesel-electric set. This can be done merely by operation of the manual transfer switch, Item H, since the diesel-electric set develops 220V, single phase, 50Hz power.

6.4 PV/Fuel Cell for the Tunisian Village

6.4.1 Description of System Elements

Exhibit 6-12, shows a single-line diagram of the system and provides a list of its basic components. The system is designed to provide approximately 5.4kW at 114 to 144VDC to a 5.0kW inverter which, in turn, will provide 220V, 50Hz, single phase power to the village.

The PV array consists of 25 of the "standard" subarrays, each initially providing nearly 203VDC from 13 modules in series. The array is designed to develop 12.2kWp, sufficient, with backup from the fuel cell, to fully serve the load as well as maintain the battery charge.

The array/battery controller also includes a battery sensing portion which maintains a continuous log of battery state by measuring input (charging) coulombs of energy and output (discharging), coulombs. This system is also capable of operating the contactor (Item E in Exhibit 6-12) when the array does not offer sufficient power and the battery is at the 80% discharge point. At this point contactor H may be closed to serve the load from the fuel cell, although load shedding may be necessary.

The alternate generator in this system is a 3.7kW fuel cell utilizing methanol and oxygen (from the air) as fuel and having a phosphoric acid electrolyte.

This particular fuel cell is being developed by the Energy Research Corporation of Danbury, Connecticut, under contract to Meradcom, Fort Belvoir, Virginia.

Advice from the Energy Research Corporation includes the following:

a. Highly portable 1.5 and 3kW units are being developed for use by the Army in remote locations.

b. Present fuel is methanol mixed with water. This is expected to be modified to liquid methanol alone. At full load, the unit uses approximately one pound (about 0.15 gallon) of methanol per kWh, or about 0.45 gallons per hour for the 3kW unit. Idling at no load, it consumes approximately one third of this amount.

c. Prototype units now being made consist of an 80 cell stack which, at .60 volts per cell produce 48 volts DC.

d. There is no problem anticipated in extending the cell stack to 217 cells to develop 130 volts DC for service to the inverter.

e. Operating temperature is 190°C and startup requires approximately 30 minutes.

f. The efficiency of the unit is approximately 30%. Thus, to develop 3kW of electric power the thermal equivalent of 10kW of methanol are used giving a residue of 23,884 BTU per hour. Of this approximately 15% is utilized for heating the reformer. This then leaves 20,300 BTU per hour which must be removed. In summer, a ventilating system moving 1880 CFM is considered sufficient to maintain a temperature rise of 5.5°C, (10°F). In the worst condition this will allow the temperature in the fuel cell room to rise to about 44°C, (110°F). The fan will impose an additional load of about 550 watts on the system.

   In winter, the waste heat may be effectively used to maintain a temperature in the battery room which would allow the batteries to operate more efficiently.

   In order to offset the power drain of the necessary ventilating system, the fuel cell capacity must be increased to 3.7kW.

g. No commercial units are available today, particularly units developing the voltage required for this PV/fuel cell conceptual design. If an industry develops, which is expected, units of the type required for this conceptual design are projected to be available in approximately five years.

At half to full load, the 3.7kW fuel cell generator will burn approximately 0.56 gallon of methanol per hour; idling at no load it will burn about 0.19 gallon per hour. The average methanol consumption is about 200 gallons per month. Since a methanol supply may be some distance away and require time to procure in quantity, use of a 1,000 gallon storage tank is assumed.

Exhibits 6-13 through 6-15 provide additional details on the PV/fuel cell hybrid design.

6.4.2 Operation

The PV/fuel cell system is designed for automatic operation.

During the day the PV array will serve the load, and either recharge the battery or maintain its charge so long as sufficient insolation exists to maintain the load demand.

During such periods the fuel cell generator will remain at idle under no load with contactor H (Exhibit 6-15) held in the open position by the battery controller. This mode of operation reduces the consumption of methanol to 1/3 of full load consumption and maintains the fuel cell generator "at the ready" for immediate load assumption. Otherwise it would require an outside source of heat over a 30 minute period to start the fuel cell generator. As discussed in Section 5.0, this mode is more cost-effective than using the fuel cell only at night and increasing battery capacity as a means of improving daytime energy availability.

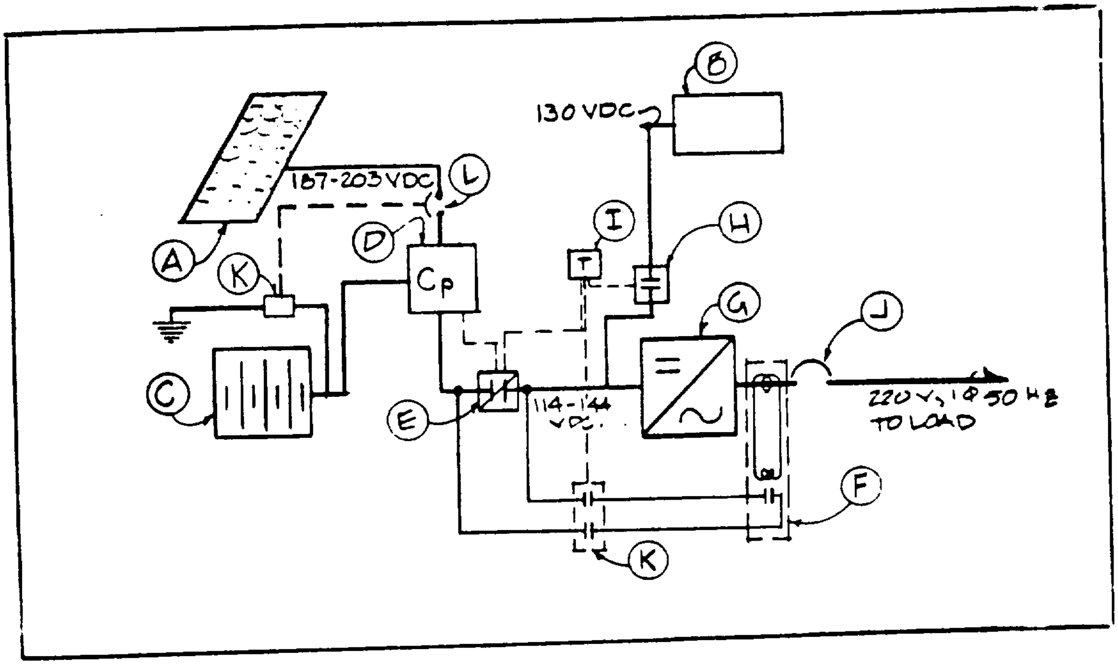


EXHIBIT 6-12

SINGLE LINE DIAGRAM OF THE TUNISIAN VILLAGE PV/FUEL CELL HYBRID

Legend:

A. PV Array: 25 subarrays - see detail of typical subarray, Exhibit 6-1.

B. Fuel Cell: Methanol-Air, 3.7kW capacity, 217 cell stack @.6V/cell provides 130VDC.

C. Battery: Lead antiomny type, 120VDC nominal, see Exhibit 6-15 for details.

D. Battery Controller: TriSolar Model MPCB-P25, maintains battery charging and supply to inverter. Maintains continuous log of battery charge and opens contactor E at 80% discharge point.

E. Contactor: 250VDC, 50A, normally closed remote control by battery controlle and time switch.

F. Load Sensor: A current transformer in the output line senses overload and causes associated relay to close allowing battery to assume part of the loa

G. Inverter: Output 220V, 50Hz to maximum 5.0kW load.

H. Contactor: 250VDC, 30A, normally open. Remote control by time switch.

I. Time Switch: With astronomic dial to operate contactors E, F & H to allow fuel cell to assist array in daylight and carry load at night.

J. Output Breaker: 250VAC, 30A trip for protection against downstream fault.

K. Ground Fault Protector: Connected from negative side of battery to ground. If ground fault is detected, trips array breaker.

L. Array Breaker: 2P, 70A, 250VDC, with shunt trip.

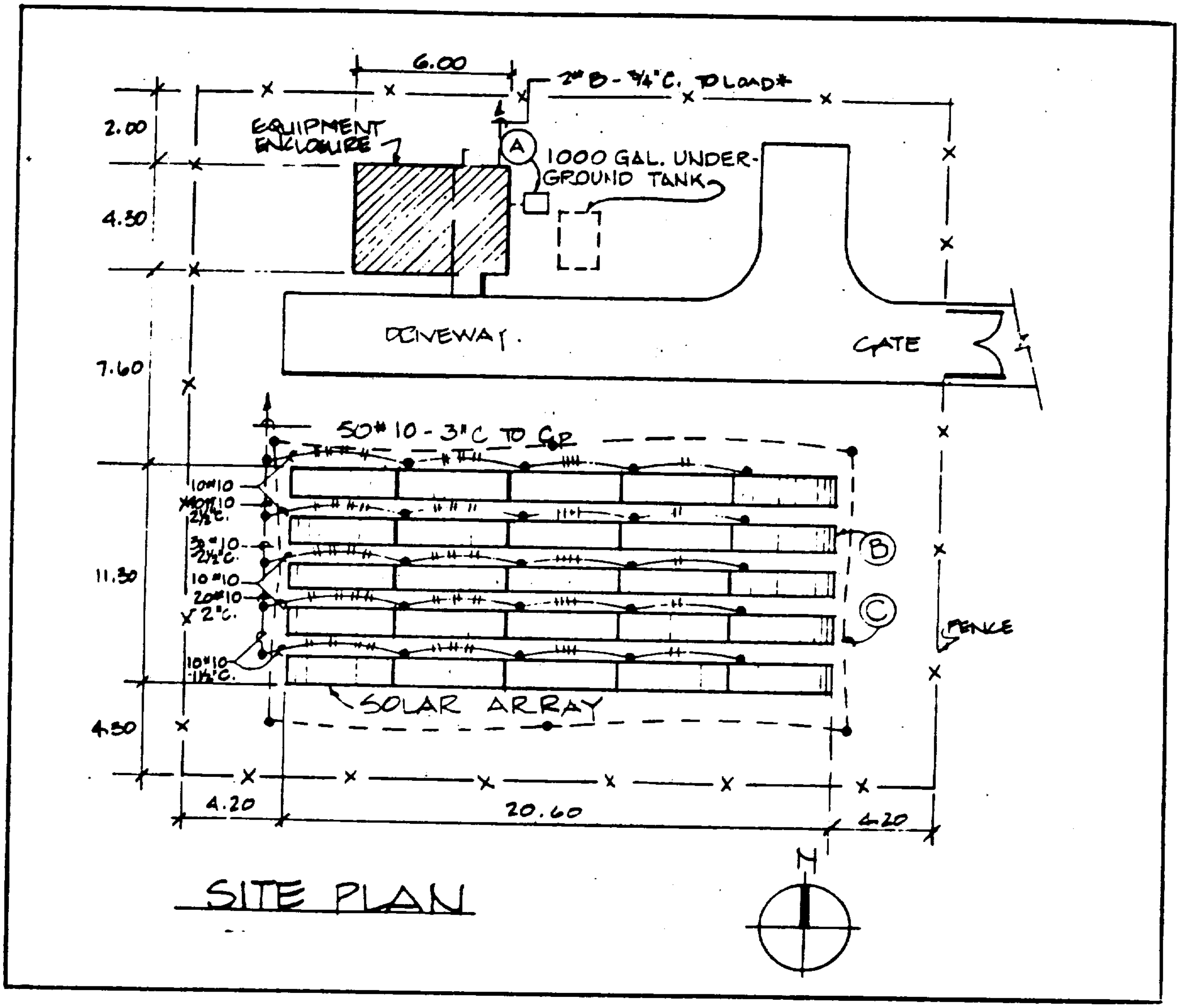


EXHIBIT 6-13

SITE PLAN FOR THE TUNISIAN VILLAGE PV/FUEL CELL HYBRID

Legend:

A. Plate or coil ground to provide maximum 25 ohms ground resistance for system ground.

B. PV array consisting of subarrays, (see Exhibit 6-1), peak watts 12, 175WP. Each subarray circuited separately to the array/battery controller.

C. Ground loop with ground rods for grounding array framework. Maximum ground resistance 25 ohms.

Notes:

1. Dimensions are in meters.

2. Conductor size may vary depending on actual length to control voltage drop and I^2R loss.

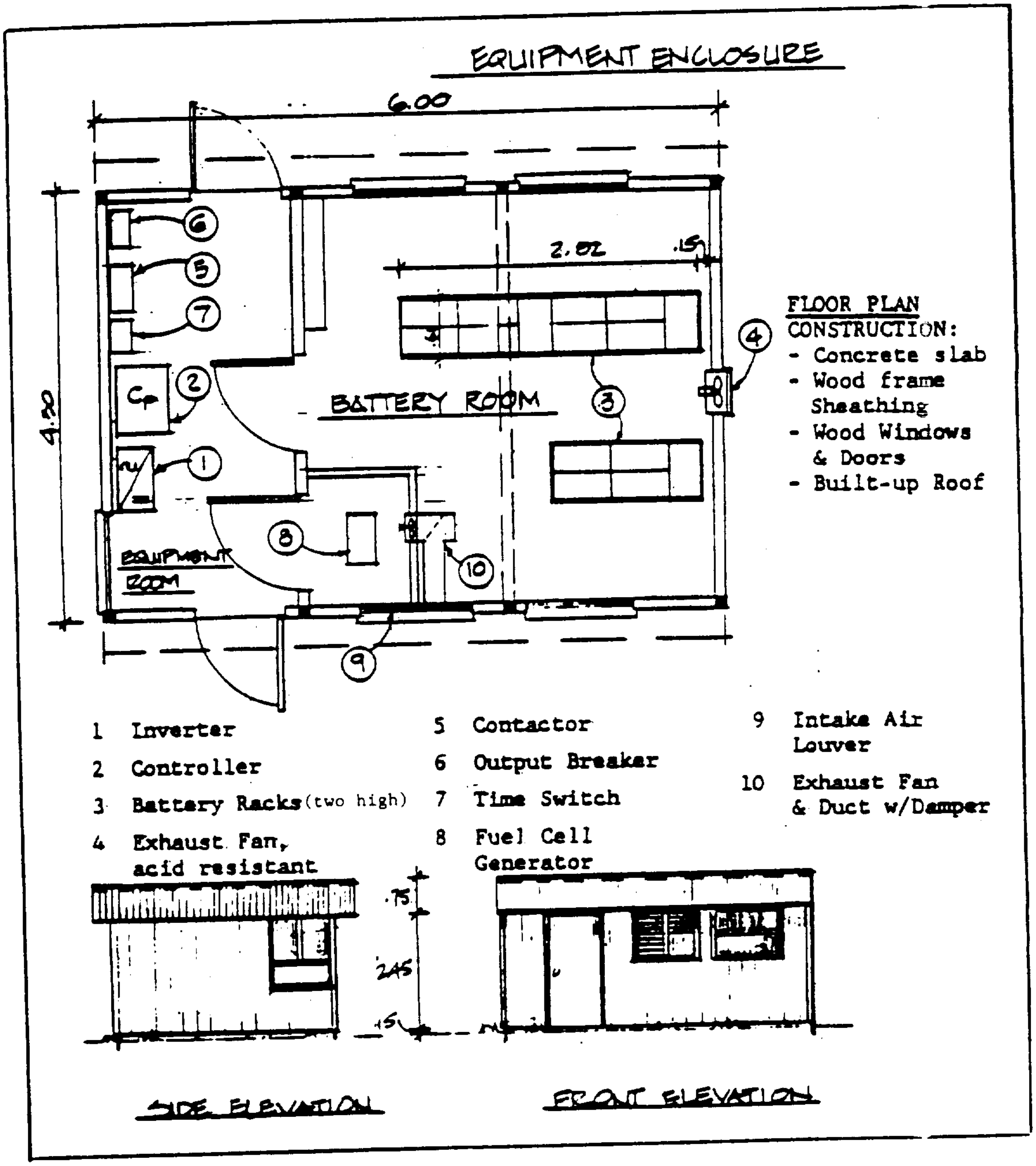


EXHIBIT 6-14

EQUIPMENT ENCLOSURE FOR THE TUNISIAN VILLAGE PV/FUEL CELL HYBRID

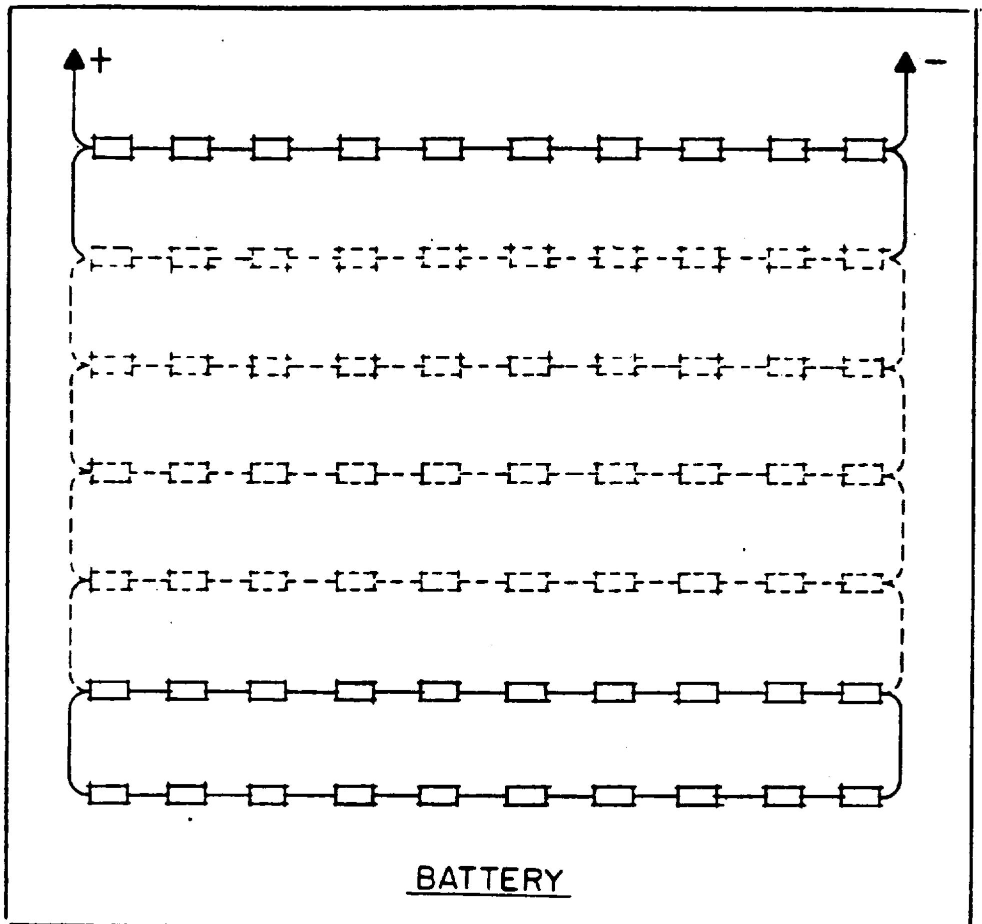


EXHIBIT 6-15

BATTERY FOR THE TUNISIAN VILLAGE PV/FUEL CELL HYBRID

Legend:

No. of Batteries in a String: 10
No. of Strings: 3
AH/String: 221 (20 hour rate)
Total AH: 663
Total kWh: 79.56

Manufacturer: Surette
Cat. No. 427EH
Size: 221AH (20 hr. rate)
2 volts/cell
12 volt/battery
Size: 20-1/16 long, 11" wide
9-3/4 high
Wet Weight: 165 pounds

When insolation decreases to a point where the PV array cannot meet the load demand, the battery supplies the difference. If this condition continues until the battery reaches 80% discharge, contactor E is opened by the battery controller, Cp, in order to avoid battery damage due to excessive discharge. At this point, contactor H may be closed to allow the fuel cell to continue to serve the load at full capacity; although, this may require some load shedding.

As evening approaches and insolation is reduced to approximately 15% of peak, the time switch (Item I in Exhibit 6-12) will operate to open contactor E and close contactor H to allow the fuel cell to serve the load directly through the inverter to the extent of its capacity.

When the night time load becomes greater than the fuel cell capacity, the situation is sensed by the current transformer in item F which causes its associated contact to close, shunting out contactor E and allowing the battery to assist in carrying the load. When the load reduces to within the capacity of the fuel cell, this contactor again opens, disconnecting the battery. This action is not possible during daylight hours since the time switch (item I) opens contactor K at the same time as it closes contactor E for the daytime operation mode.

6.5 PV/Wind System for Utirik Island

6.5.1 Description of System Elements

Exhibit 6-16 shows a single-line diagram of the system and provides a list of basic components. This system is designed to provide DC power at 120 volts to the village to support a maximum load of 3.5kW.

The PV array consists of five of the "standard" subarrays, each initially providing nearly 203VDC from 13 modules in series. The array is designed to develop 2.4kWp, sufficient, with the wind generator, to fully serve the load as well as charge the battery.

The battery controller, Cp, also includes a battery sensing section measuring coulombs of energy of charge and coulombs of energy of discharge, thus sensing at all times the state of charge of the battery. This section of the controller also operates the contactor (Item F in Exhibit 6-16) to disconnect the battery when it reaches its maximum discharge point. This of course presumes that neither the PV array nor the wind generator are producing sufficient power to maintain the system without further battery discharge.

The battery controller, Cp, also includes circuitry to restrict charging of the battery by the PV array and/or the wind generator to periods when excess energy is available, (i.e. when load demand is met). In the above case, contactor F is opened to prevent battery damage. When sufficient power subsequently becomes available from the PV array and/or the wind generator, this circuitry allows the contactor to again close to serve the load. This prevents any possibility of "hunting", i.e. intermittent operation of the contactor as a result of partial recharging of the battery. In the interim period, before power builds up sufficiently to serve the load, available power goes to battery charging.

The wind generator controller, Cw, (Item E in Exhibit 6-16) accepts a wide range of voltage output from the wind generator and down converts it to the same voltage as received by the battery controller section of Item D. In this manner, varying D.C. voltages from both the PV array and the wind generator are made compatible and both serve the battery and the load in a controlled manner.

The wind generator (Item B in Exhibit 6-16) is rated at 3.5kW at a wind speed of 11mps. It consists of a housing containing a permanent magnet alternator driven by a three bladed propeller approximately 5m in diameter. A rectifier is provided to serve the system with direct current. Cut-in wind speed is approximately 4.5mps and the device will generate full power at about 11mps. Aerodynamic blade stall occurs at about 13.5 mps.

It is noted that the output voltage of a wind generator decreases with increasing load and increases with increasing wind speed. Neither relationship is linear and varies with different manufacturers. For this reason this study assumes the use of a wind generator voltage controller of established compatibility with the battery controller rather than the wind generator manufacturer's voltage regulator.

A 20m tower has been selected. This should be high enough to avoid wind disturbance from nearby buildings and trees. It also provides a minimum height above ground of approximately 15 meters for the rotating blades. This is considered sufficient to avoid any possible hazard.

The battery contactor (Item F in Exhibit 6-16) is only for battery protection. As noted above, it is opened by the battery controller only when necessary to avoid damaging discharge.

The output switch and fuse is for disconnecting the system from the load in case of a dangerous "down stream" overload or short circuit in the power distribution system or load devices.

Exhibits 6-17 through 6-19 provide additional detail on the PV/wind hybrid system for Utirik.

6.5.2 Operation

The PV/wind system is designed for automatic operation.

At any time during the day or night when there is sufficient wind to allow the wind generator to produce over about 185 volts at

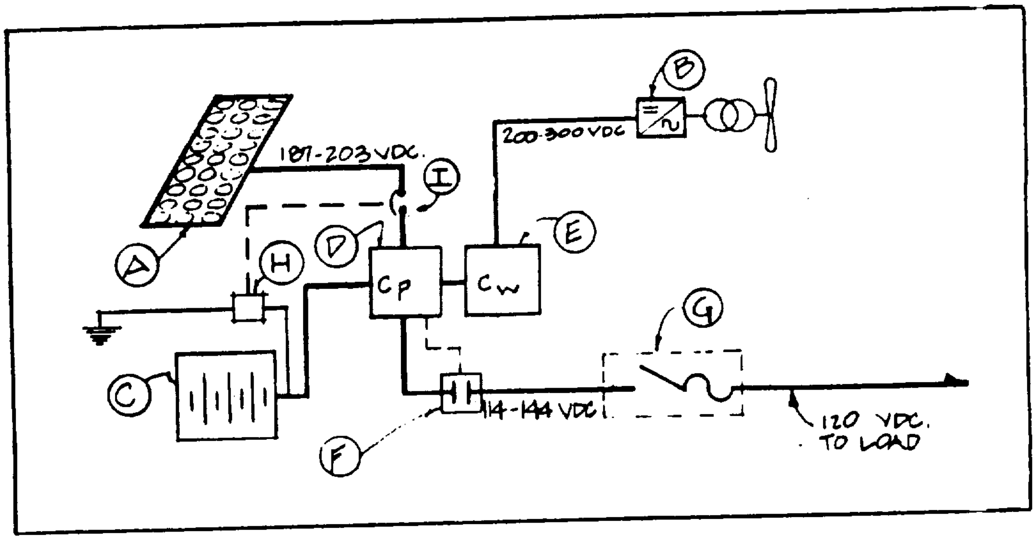


EXHIBIT 6-16

SINGLE LINE DIAGRAM OF THE UTIRIK PV/WIND HYBRID

Legend:

A. PV Array: 5 subarrays - see detail of typical subarray Exhibit 6-1. Voltage: 187-203, peak wattage: 2,434.

B. Wind Generator: Wind generator with 5m blade, permanent magnet rotor and rectifier. 3.5kW rating to develop 200 to 300VDC with 18A load and wind speeds from 4.5m/s to 13m/s.

C. Battery: Lead antimony type, 120VDC nominal. See Exhibit 6-19 for details.

D. Array/Battery Controller: TriSolar type MPCB-P5 maintains battery charging/inverter input voltage, tracks arrays at peak power point, maintains continuous log of battery charge, disconnects battery at 80% discharge point, reconnects battery when charging energy is available.

E. Wind Generator Controller: TriSolar type MPC-P-7. Operates in conjunction with Cp to maintain battery at indicated voltage range.

F. Battery Contactor: Rated 250VDC, 30A, remote control by Cp.

G. Output Fused Switch: 2 pole, 30 ampere fused for protection of maximum load.

H. Ground Fault Protector: Connected from negative side of battery to ground. If a ground fault is detected, breaker I is tripped.

I. Array Breaker: 2P, 20A, 250VDC, with shunt trip.

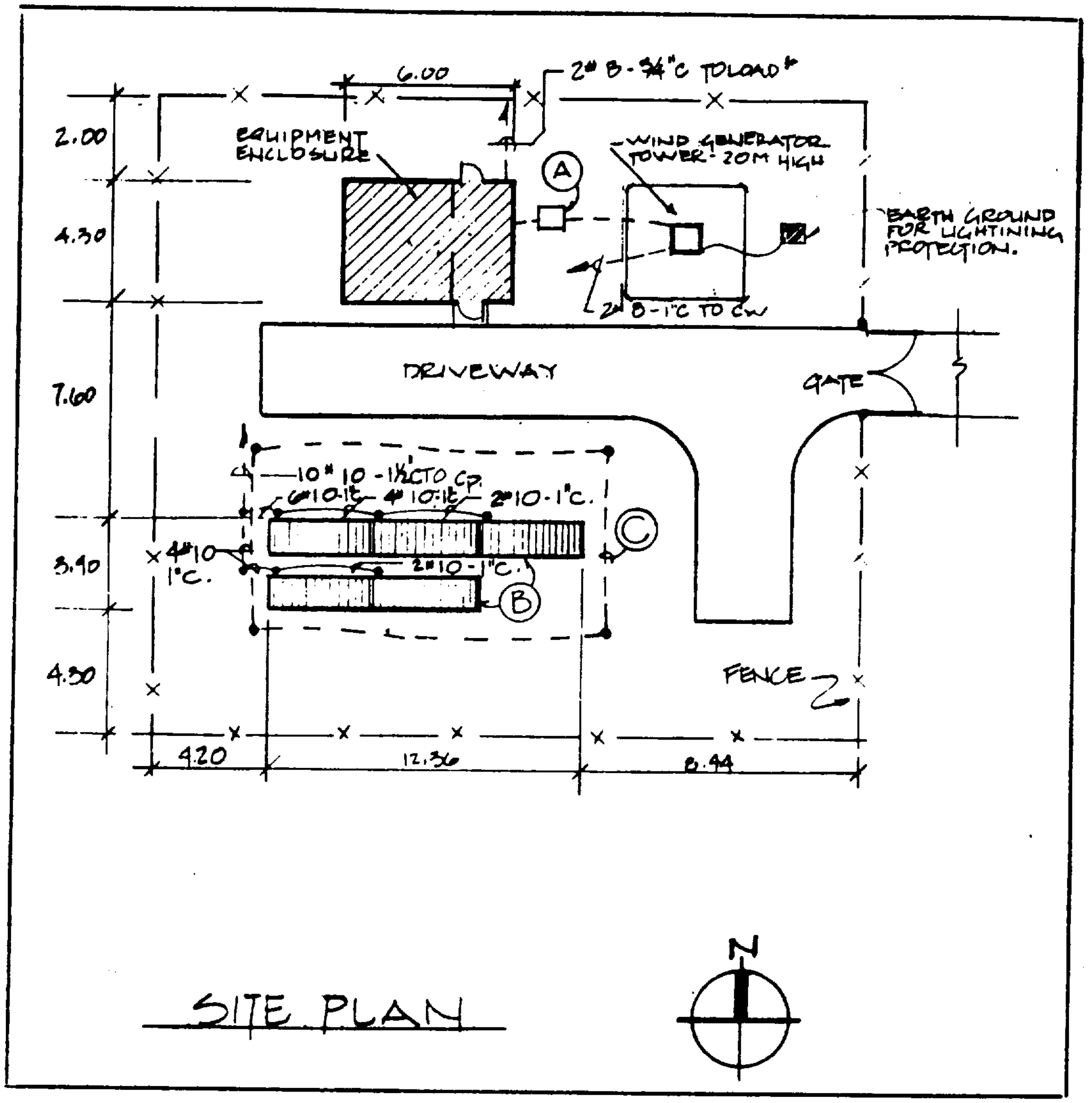


EXHIBIT 6-17

SITE PLAN DIAGRAM FOR THE UTIRIK PV/WIND HYBRID

Legend:

A. Plate or coil ground for lightning protection and system grounding. Maximum ground resistance 25 ohms.

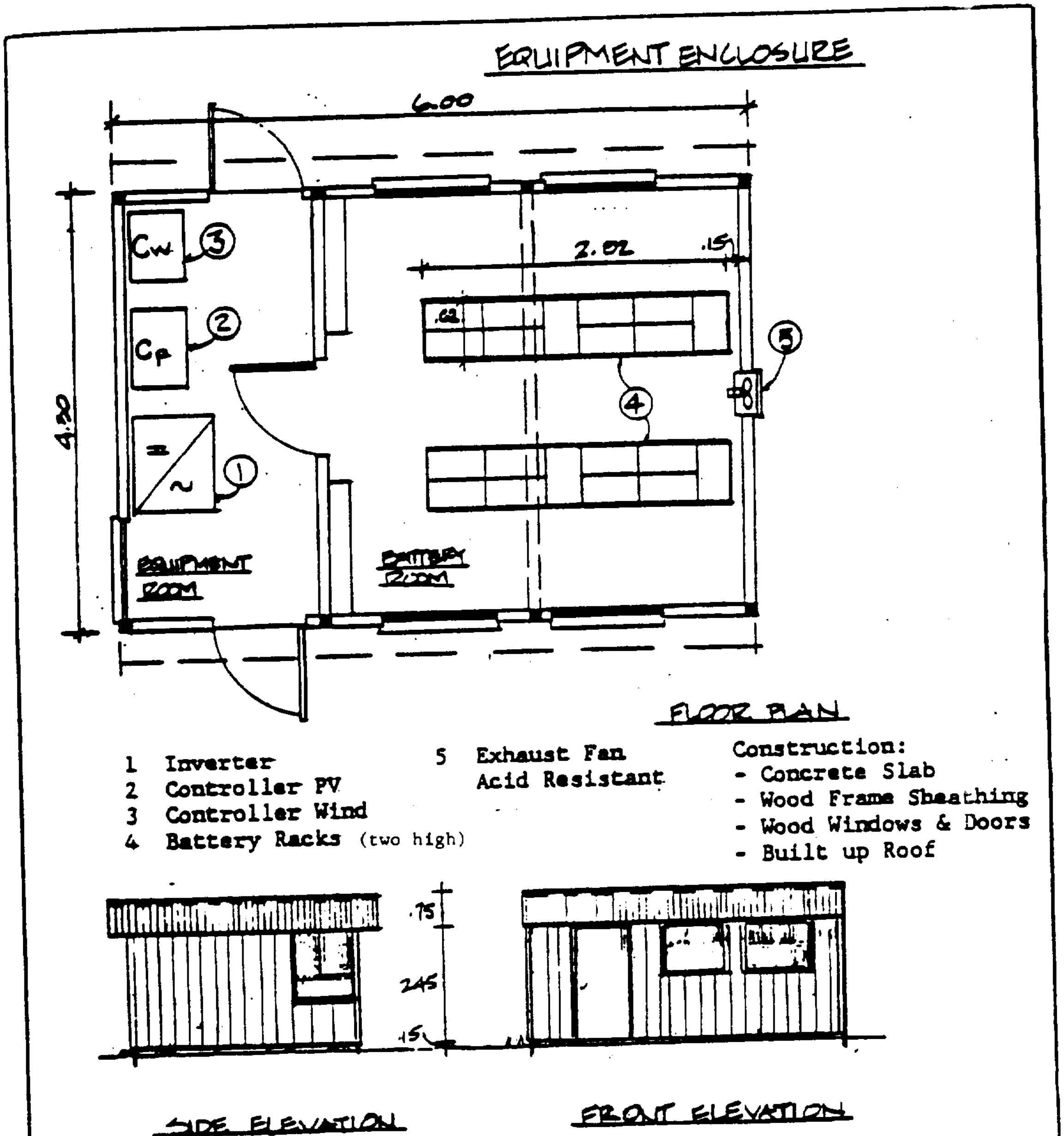
B. PV array consisting of five subarrays, (see Exhibit 6-1). Peak watts 2,434Wp. Each subarray connected separately to the array battery controller.

C. Ground loop with ground rods for grounding array framework. Maximum ground resistance 25 ohms.

Notes:

1. Dimensions shown are in meters.

2. Conductor size may vary depending upon actual length in order to control voltage drop and I^2R loss.



Dimensions shown are in meters.

EXHIBIT 6-18

EQUIPMENT ENCLOSURE FOR THE UTRIK PV/WIND HYBRID the applied load, it begins to provide power to the battery controller.

When sunlight is sufficient, the PV array also provides power and the two sources in parallel serve the battery controller which, in turn, charges the battery with the energy in excess of that required by the load.

When neither insolation nor wind is sufficient, the battery provides necessary energy at 120V to maintain the load until the battery reaches a discharge point of 80%, (20% of charge remaining). Sensing this, the battery controller opens the contactor utilizing remaining battery energy and holds it open until either the wind generator or the PV array, or both, have restarted to provide sufficient energy to again sustain the load. The battery controller then allows the contactor to reclose, and increasing energy from the array and wind generator recharges the battery. In the meantime, available energy from the array and/or the wind generator is utilized for battery charging.

It is not necessary to provide blocking diodes between either the wind generator or the PV array and their respective controllers since the controllers perform this function.

6.6 Estimated Capital Cost of the Hybrid Systems

The following cost estimates include the following assumptions:

- PV modules at $5.00 per Wp.
- Fuel cell generator $6,000.
- Other equipment per manufacturers 1983 costs.
- Cost of spares is not included.
- Installation, (labor), 1983 costs in the United States.
- Cost of Labor (Burden) can vary widely depending on site location, type of labor, (local or imported), living conditions, etc. This can increase labor costs by 25% to 125%. The amount shown, 35%, is considered a median value in the U.S.A.

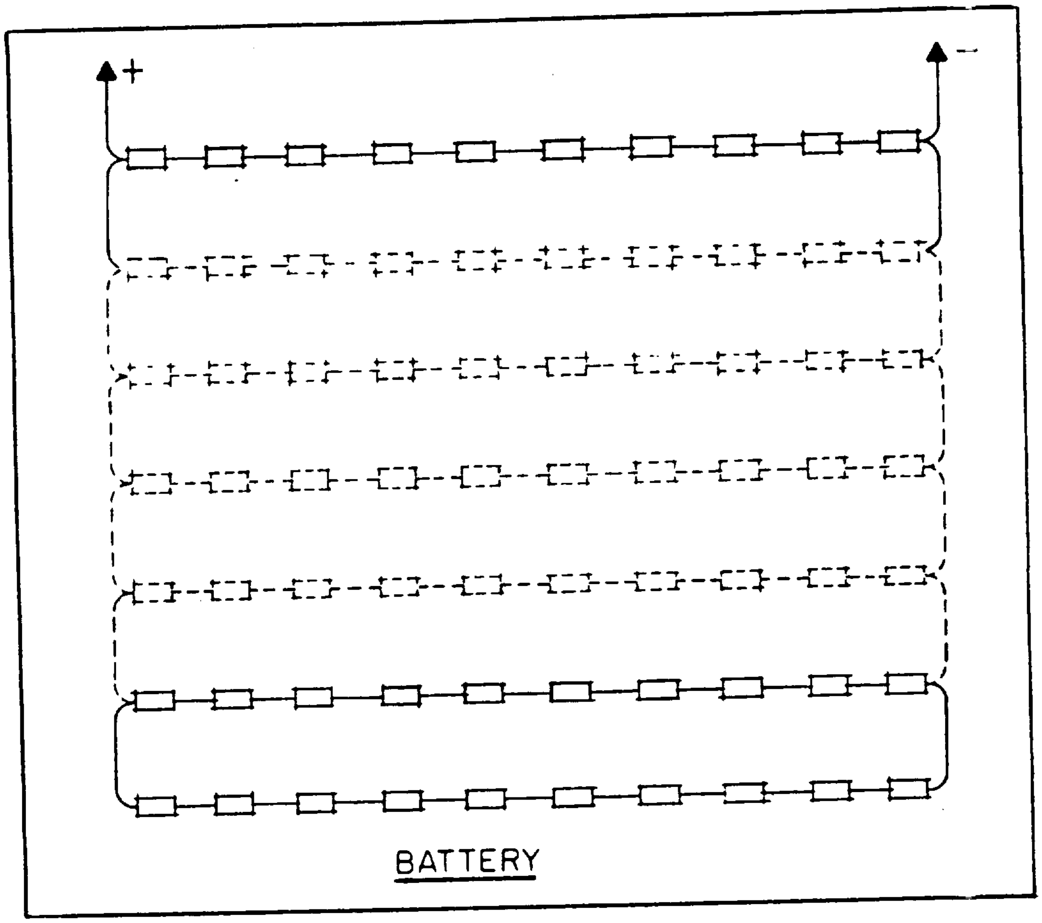


EXHIBIT 6-19

BATTERY LAYOUT FOR THE UTIRIK PV/WIND HYBRID

Legend:

No. 12V Batteries in a String: 10
No. of Strings: 4
AH/String: 221 (20 hour rate)
Total AH: 884
Total kWh: 106

Manufacturer: Surrette
Cat. No. 427EH
Size: 221 AH (20 hr. rate)
2 V per cell (nominal)
12 V per Battery
Size: 20" long, 11" wide
9-3/4 high
Wet Weight: 165 pounds

6.6.1 Tunisian Village PV/Wind System Costs

Item	Equipment	Installation
PV Array	$ 34,100.	$ 7,000.
Wind Generator & Tower	30,500.	3,500.
Battery with Caps & Rack	18,500.	4,000.
Battery Controller	9,150.	750.
Wind Generator Controller	5,705.	250.
Inverter	4,055.	150.
Contactor	1,200.	75.
Output Circuit Breaker	75.	25.
Equipment Enclosure	3,000.	2,000.
Driveway	1,350.	600.
Fence	3,600.	1,300.
Lightning Protection	150.	250.
Wiring	1,200.	3,200.
	112,585.	23,100.
Cost of Labor, (Burden), @ 35% of installation		8,085.
		112,585.
		$143,770.
G&A O.H. @ 15%		21,566.
		$165,336.
Profit @ 10%		16,534.
		$181,869.
Shipping costs		15,000.
TOTAL		$196,869.

6.6.2 Tunisian Village PV/Diesel System Costs

Item	Equipment	Installation
PV Array	$ 60,840.	$ 12,500.
4kW Diesel-Electric Set	4,000.	500.
Diesel Engine Controls	2,875.	400.
Battery with Caps & Rack	6,830.	1,475.
Battery Controller	15,330.	1,250.
Inverter	4,055.	150.
50A Contactor	1,200.	75.
60A Manual Transfer Switch	275.	100.
Rectifier	1,500.	250.
Time Switch	125.	50.
Output Circuit Breaker	75.	25.
Equipment Enclosure	2,800.	1,800.
Driveway	1,350.	600.
Fence	3,750.	1,350.
Fuel Tank, 275 gallon	150.	61.
Wiring, Conduit, etc.	2,200.	5,100.
	108,155.	26,136.
Cost of Labor, (Burden), @ 35% of installation		9,148.
		108,155.
		$143,439.
G&A O.H. @ 15%		21,516.
		$164,954.
Profit @ 10%		16,495.
		$181,450.
Shipping costs		15,000.
TOTAL		$196,450.

6.6.3 Tunisian Village PV/Fuel Cell System Costs

Item	Equipment	Installation
PV Array	$ 60,840	$ 12,500.
Fuel Cell Generator	6,000.	1,500.
Output Controls	2,875.	400.
Battery with Caps & Rack	6,830.	1,475.
Battery Controller	15,330.	1.250.
Inverter	4,055.	150.
Two 50A Contactors	2,400.	150.
Time Switch	125.	50.
Output Circuit Breaker	75.	25.
Equipment Enclosure	2,400.	1,600.
Driveway	1,350.	600.
Fence	3,750.	1,350.
Fuel Tank, 1,000 gallon	3,000.	4,800.
Wiring	1,800.	4,800.
	$ 110,830.	$ 26,150.
Cost of Labor, (Burden), @ 35% of installation		9,153.
		110,830
		$146,133.
G&A O.H. @ 15%		21,920
		$168,052.
Profit @ 10%		16,805.
		$184,858.
Shipping costs		15,000.
TOTAL		$199,858

6.6.4 Utirik Island PV/Wind System Costs

Item	Equipment	Installation
PV Array	$ 12,200	$ 2,500.
Wind Generator & Tower	9,700.	2,500.
Battery with Caps & Rack	9,150.	2,000.
Battery Controller	3,920.	300.
Wind Generator Controller	4,135.	250.
Contactor	800.	75.
Output Fused Switch	50.	25.
Equipment Enclosure	2,050.	1,400.
Driveway	1,350.	600.
Fence	3,000.	1,100.
Lightning Protection	150	250.
Wiring	800.	2,200.
	$ 47,305.	$ 13,200.
Cost of Labor, (Burden), @ 35% of installation		4,620.
		47,305.
		$ 65,125.
G&A O.H. @ 15%		9,769.
		$ 74,894.
Profit @ 10%		7,489.
		$ 82,383.
Shipping costs		12,000.
TOTAL		$ 94,383.

6.7 General Maintenance Requirements

6.7.1 PV Array

At two week intervals, the array should be washed down with a hose or other convenient means to remove dust, bird droppings, etc.

No other periodic maintenance should be necessary.

6.7.2 Wind Generator

At two week intervals, the generator should be halted with the mechanical device provided and lubrication checked. The housing should be opened and the mechanism visually checked. If abnormal signs such as discolorations, broken connections, worn bearing races, etc., are noted, necessary maintenance should be undertaken in accordance with manufacturers instructions.

6.7.3 Battery

Each month the water level in each cell should be checked and renewed with distilled water as required. At the same time, all terminals should be checked for possible corrosion, and cleaned with a mild base such as bicarbonate of soda. If corrosion is more than minor, the battery should be temporarily removed and, in a place where drainage is available, flushed with a solution of baking soda and water, rinsed with clean water, dryed with a clean cloth, terminals greased and battery reinstalled.

Every three to four months each cell should be checked with a hydrometer to ensure they are charging evenly. If specific gravities are found to vary more than a few percent, the battery should be recharged at the maximum rate, (2.4V per cell) until it gasses freely and is restored to full charge with specific gravity of 1.250 at 27.6°C. Water may be added at this time to bring the liquid level to the bottom of the filler hole cylinder. After equalization, allow time for any added water to diffuse through the electrolyte and recheck all cells with the hydrometer to detect any cell which has failed or is about to fail. This will be evidenced by a specific gravity reading below 1.150.

Since the battery controller along with input from the PV array and/or the wind generator is capable of charging at 2.4 volts per cell, this procedure may be required only rarely.

6.7.4 Battery Controller

The battery and wind generator controllers should require little maintenance. They should be kept free of dirt and other foreign material and the control room in which they are located should be well ventilated and kept clean.

There are three basic components in these controllers; Power Module, Control Board and State of Charge Board. If one fails a technician can locate it with an ordinary multi-meter. If a technician unavailable, the guide manual must be consulted for directions. According to the manufacturer it takes about five minutes to remove the defective circuit board and insert a replacement after it has been identified. To this end, a supply of each of the three types of circuit boards should be kept on hand. The MTBF of the battery controller is 29,100 hours.

6.7.5 Inverter

The inverter, like the battery controller, is a solid state device. However, it is more complex in circuitry, and circuit boards are not as readily replaceable. Further, the MTBF is lower, variously estimated at between 15,000 and 20,000 hours. It is, therefore, recommended that a spare inverter be kept on hand, since repair of this equipment requires expertise not normally expected to be found at the location under consideration.

The spare should be kept in a sealed container to ensure that it is not unwittingly damaged by foreign material. Under these conditions the shelf life should be almost indefinite.

6.7.6 Diesel-Electric Set

Of all the equipment in any of the systems, the Diesel-Electric Set probably requires the greatest amount of maintenance.

The manufacturer's maintenance recommendations are based strictly on hours of operation and are geared to standby power machines which are inoperative most of the time. Barring a major emergency, operation of 200 hours per year is considered average; whereas, in the case of the Tunisian village, the diesel-electric set is expected to operate over 3,000 hours per year. The following table takes this into account. when providing a set of guidelines for the care and operation of the Diesel-Electric Set.

Period		Operation
Daily	a.	Visually inspect for obvious problems, leaking oil, undue vibration, etc.
	b.	Check liquid levels Fuel oil in storage tank. Lube oil in crankcase.
Weekly	a.	Check air cleaner, blow out or replace if necessary.
	b.	Check starting battery for specific gravity and liquid level, each cell.
Monthly	a.	Clean governor linkage.
	b.	Change lube oil and filter.
	c.	Clean primary fuel filter.
	d.	Inspect anti-flicker and centrifugal switch breaker points. Replace if necessary.
Quarterly	a.	Clean collector rings.
	b.	Check control systems.
	c.	Clean alternator, grease main bearing, (if not sealed type).
Semiannually	a.	Clean oil passages and replace secondary fuel filter.
Annually	a.	Check valve clearances.
	b.	Grind valves and remove carbon if necessary.
	c.	Remove and clean oil base, check injector nozzle pressure and spray pattern, replace nozzles as necessary.
	d.	Check injector pump for leakage, replace gaskets and seals as necessary.

For purposes of these maintenance operations, spare parts and special tools should be provided per the manufacturers recommendations for perhaps a two year period along with a proper cabinet for their storage.

6.7.7 Fuel Cell Generator

This equipment, although not as yet fully developed, has already gained a reputation for reliability.

The manufacturer states that the fuel cell stack itself will probably require replacement at five year intervals; Also, during these periods only minimal maintenance will be required.

As an indication of the expected reliability, one Army requirement is that the units operate for a minimum of 5,000 hours under all conditions with no maintenance whatsoever. Obviously to accomplish this, they must be designed for a much greater life than 5,000 hours.

6.7.8 Miscellaneous Equipment

This category includes the smaller, more reliable items such as exhaust fans, contactors, time switches, etc. which for the most part require only occassional cleaning. Fans not equipped with sealed bearings also require oiling at quarterly or semiannual intervals.

7.0 FURTHER DEVELOPMENT REQUIREMENTS

The cost effectiveness of the PV hybrid systems can be enhanced with further system and hardware developments. The designs discussed in the previous sections are based on the current state of the art, with only a mild extrapolation of the cost and performance of the PV modules. There are many technological improvements possible that would make the systems more attractive. The purpose of this section is to discuss some improvements that seem to be attainable within the near future.

Some of the improvements have little to do with PV hybrids per se. For example, any major reduction in the cost or improvement in the efficiency of the PV modules would make both PV-alone and PV hybrid systems more cost effective. Both would also profit if battery lives were extended or if control system reliabilities were increased. Similarly, wind systems as well as PV-wind hybrids would benefit if the wind system were cheaper or more reliable. PV diesels would benefit if the startup reliability of diesels were improved from the current 98%. Because most of these improvements are well known in conjunction with the non-hybrid systems, the current discussion will focus on improvements that pertain more directly to hybrid systems.

Potential improvements in hybrid systems are discussed below under the following categories: (1) system design and analysis techniques; (2) system configuration and operation; and (3) hardware design. Improved design and analysis techniques would permit design with a smaller margin and better economic evaluation. The systems advancements can be in terms of operating sequences and control strategies. The hardware improvements would come primarily from better control systems.

7.1 System Design and Analysis

The sizes of the components (e.g. battery or PV array size) in the power system could probably be reduced if the component models more nearly simulated the performance of the components. For example, at present, batteries are characterized by an average efficiency rather than an instantaneous efficiency. Currently available hourly simulation procedures, such as SOLCEL[1], characterize the batteries with more realistic curves of voltage versus state of charge for various charging rates; however, the curves may be too inaccurate. The systems analyses reported herein would not be greatly affected by the more rigorous battery performance models; however, if some of the more advanced control schemes discussed below were implemented, the difference between model and actual performance could be substantial.

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1 Hoover, E.R., "SOLCEL-II: An Improved Photovoltaic System Analysis Program," Sandia Laboratories, SAND79-1785, February 1980.

The AC power system design might be different if the total system were optimized, including the load, the motors and transformers. The designs presented herein are based on using an inverter with a modified square wave output, having 20% total harmonic distortion. To accommodate other than a sine wave, one motor transformer manufacturer recommended that the transformers be oversized by 30% and the motors, by 20%. In addition, the motor efficiencies are lower by as much as the total harmonic distortion (20% for the modified square wave). If the total system were optimized, including the effect of wave form on the size and performance of the motor loads, a higher-cost inverter may be cost effective. For example, a 6-kW ferroresonant-transformer inverter, which is highly fault tolerant, can be purchased for $11,000, as compared to $4,000 for the 5-kW modified-square-wave inverter. The difference of $8850 (after markups) may be more than compensated by the reduction in total harmonic distortion to only 5%. However, neither a model nor field data are available to assess this tradeoff. There could be a power-system cost saving of as much as 15% due to the higher motor efficiencies attainable with an inverter with only 5% distortion.

In addition to the above improvements, the hybrid models should be enhanced to allow them to become design aids. Specific improvements recommended include utilizing actual PV module specifications, using variable instead of constant inverter efficiency and enabling the model outputs to be directly usable by design engineers. In particularly, several improvements should be made to the PV/engine model. These include the following: enabling the engine to charge the batteries even if the battery is not at its lowest charge limit, testing the use of battery state-of-charge as an engine controller, and allowing seasonal change in operating protocol.

The other area for system design and analysis improvement is in developing a better system reliability estimation procedure. The present piecemeal method is inadequate and a procedure that can integrate resource and demand uncertainties, and equipment reliabilities should be devised. An attempt was made in this study to develop an integrated reliability estimation procedure, however further development is required.

7.2 System Configuration and Operation

If the battery had greater capacity, the batteries could operate between 20% and 90% state of charge, thereby achieving an input/output efficiency of as high as 95%. A smaller battery would cycle between 20% and 100% and have an input/output efficiency of less than 85%, because high charging voltages are needed to achieve 100% state of charge. Therefore, optimal sizing and managing of the battery could permit a reduction in the PV array size of about 10%. A timer would be needed by which the batteries would be charge equalized, possibly every two weeks. Charge equalization could be accomplished by setting the controller output voltage temporarily to 2.4 volts instead of 2.2 volts per cell.

Additional gains in the system performance could be realized if different operating strategies were followed during different seasons of the year. A programmable controller would facilitate such operation. For example, during the sunny season, the batteries could be discharged to a 30% state of charge before the alternate generator came on. In many cases with this strategy, the alternate generator may not be needed at all during the sunny season, if the battery is optimally sized. A 50% state of charge may be more suitable in the low insolation season. A seasonally adjusted operating strategy might also find the fuel cell operating continuously only in the low isolation season, at a great saving in fuel. Seasonal strategies for small systems could include adjustable array tilt angle.

Most of the power controllers can tolerate overloads of approximately 25%, which may be insufficient for motor starting in a village with one or two large motors. Some load-control strategies might be developed that prevent simultaneous starting of the motors. In the designs reported herein, it has been assumed that, with diversity included, the 25% overload would not be exceeded. If such were not the case, the power controller would need to be oversized and its average efficiency would be less. As an alternative, Type F motors[1] should be considered, provided there would be sufficient logistical support for replacing these non-standard motors. For the representative loads examined, the 25% overload capability is sufficient, so the present cost estimates would not be decreased by the use of Type F motors.

The wind system in the current design might deliver more energy with an alternative design. For example, more energy might be extracted if the power controller could be designed to maximize the output of the wind system. The output would then be integrated with the PV system output. The PV system controller would then optimize the combined output. By having a separate controller for the wind system, so that the wind-system voltage equals that of the PV array, the current designs have approximated this optimization. However, a separate peak-power tracker for the wind system would probably be better--assuming the stability of two peak-power trackers operating together could be assured. Probably a master unit would be required that controls both peak-power trackers simultaneously. The master unit might be a microprocessor-based power controller.

The diesel system might benefit from multiple engines. For example, instead of a 6-kW diesel, with potential startup and/or maintenance problems, two or three 3-kW engines might be used. The system's initial cost would be higher but the system availability would improve, especially in remote areas where major engine parts

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1 NEMA Type F motors have starting torques only slightly higher than running torques. Therefore they have relatively low starting currents.

are not stocked. The smaller engine might also permit the operation of the engines at higher load, because the number of engines operating could be selected to meet the load.

Three-way combinations could be considered for the hybrids with two energy sources that depend on the weather: PV-wind and PV-hydro. A portable engine could be used during maintenance periods. A stationary engine could be used only on those rare occasions when neither renewable resource was available. The engine would add little to the system cost and almost nothing to the operating cost, but it would permit the sizes of the array, battery and generator to be considerably reduced because there would be no need to design for extreme weather patterns.

7.3 Hardware

Because the discussion has been limited to improvements pertinent to the hybrid aspects of the systems, almost all of the improvements in hardware considered are in the power conditioning and control system (PCC). The pulse-width-modulated (PWM) controller used in the current designs is almost as efficient as possible. However, some additional gains would be realized if a higher array voltage was used. The PCC has a fixed voltage drop which becomes less significant as the system voltage increases. The cost of the PCC might be reduced if power transistors were available that had a higher current capacity than those used in the commercially available systems.

A microprocessor controller could probably be gainfully employed. For example, the microprocessor could be programmed for seasonally optimized system operation for maintaining the battery state of charge between 20% and 90% with biweekly charge equalization, for load shedding, and for operating the battery state of charge with temperature and history corrections.

The current PV/diesel designs requires rectifying the AC power generated by the diesel and then inverting it. This AC/DC/AC conversion with the resulting 10% loss in efficiency is needed, since an inverter that can be both self- and line-commutating is not available. A PCC that can control the more complex system and an appropriate inverter are needed if the 10% loss is to be avoided.

Some hardware improvements could be achieved in the battery system. A monitoring system is still needed by which the condition of each cell can be determined without having to visually inspect it. For example, a flag could be raised (or "set" in a microprocessor) so that any battery with a low state of charge relative to its neighbors would be marked. Although the wiring might be excessive, such a flag system could be used to automatically connect the standby battery into the circuit in the correct location. If batteries could be replaced automatically, inspection and maintenance costs could be reduced considerably.

Finally, the operating strategies for the fuel-cell hybrid were determined largely because this unit required 30 minutes to start. Thus, in the designs, the fuel cell is operated continuously on standby, because startup times are so long. If a fuel cell could be operated at room temperatures, the startup time could be greatly reduced. The fuel consumption would consequently be reduced, and the system would be economically more attractive. Since solidelectrolyte cell has a lower efficiency, but operates cold, it might be a suitable candidate for this application.

APPENDIX A

SOURCE CODE LISTINGS
OF COMPUTER PROGRAMS

TABLE OF CONTENTS

PROGRAM LISTINGS

HOURLY INSOLATION GENERATOR

```
C**********************************************************************
C        PROGRAM TO GENERATE HOURLY SOLAR RADIATION DATA.              *
C        DAILY AVERAGE INSOLATION IS COMPUTED USING THE METHOD         *
C        DESCRIBED IN EXHIBIT 11.1-1 (PAGE 11-2) OF                    *
C        "PHOTOVOLTAIC STAND ALONE SYSTEMS"                            *
C        HOURLY INSOLATION VALUES ARE COMPUTED FROM DAILY              *
C        AVERAGES USING THE EQUATION GIVEN IN "ALTERNATE POWER         *
C        SOURCES FOR REMOTE SITE APPLICATIONS", PAGE 58, EQ 3.5        *
C                                                                      *
C        FOR EACH DAY OF THE YEAR, A RANDOM CLEARNESS INDEX (KH)       *
C        IS GENERATED USING THE BETA DISTRIBUTION WITH PARAMETERS      *
C        PP AND QQ (CALL GGBTR)                                        *
C**********************************************************************
      DIMENSION
     +    A(72),          AVGKH(12),      HRINS(24),      IOPT(5),
     +    IW(132),        NDAY(12),       RANDN(1),       TAB(10),
     +    W(132)
      DOUBLE PRECISION
     +    DSEED
      DATA
     +    IOPT /0,1,0,0,1/,
     +    NDAY /31,59,90,120,151,181,212,243,273,304,334,365/
      DSEED=1351931.
      WRITE (6,70)
      READ (5,*) ISDEC
      IF (ISDEC.EQ.1) WRITE (6,80)
      IF (ISDEC.EQ.1) READ (5,*) DSEED
      WRITE (6,90)
      READ (5,*) (AVGKH(I),I=1,12)
      WRITE (6,100)
      READ (5,*) XLAT
      WRITE (6,110)
      READ (5,*) RHO
      WRITE (6,120)
      READ (5,*) PHI
      RADFAC=3.141592/180.
      ANFAC=(360./365.)*RADFAC
      HRFAC=24./3.141592
      COSLAT=COS(XLAT*RADFAC)
      COSPHI=COS(PHI*RADFAC)
      SINLAT=SIN(XLAT*RADFAC)
      COSLPH=COS((XLAT-PHI)*RADFAC)
      TANLPH=TAN((XLAT-PHI)*RADFAC)
      XFACT=COSLPH/COSLAT
      SQRTPI=(SQRT(3.141592)-1.)/3.141592
      SQPI=SQRT(3.141592)
      SINDCL=SIN(23.45*RADFAC)
      TANLAT=TAN(XLAT*RADFAC)
      MON=0
      IDM=0
      WRITE (6,130)
      DO 60 IDAY=1,365
      IF (IDAY.LE.IDM) GO TO 10
      MON=MON+1
```

```
      IDM=NDAY(MON)
      XKH=AVGKH(MON)
      CALL PQ (XKH,PP,QQ)
      WRITE (6,140) MON,IDAY,XKH,PP,QQ
   10 CALL GGBTR (DSEED,PP,QQ,1,RANDN)
      DAYKH=RANDN(1)
      ITL=IFIX(DAYKH*10.)+1
      IF (ITL.GT.10) ITL=10
      TAB(ITL)=TAB(ITL)+1
      SINDEL=SINDCL*SIN((284+IDAY)*ANFAC)
      DEL=ASIN(SINDEL)
      COTHSS=-TANLAT*TAN(DEL)
      THSS=ACOS(COTHSS)/RADFAC
      COTHTS=-TANLPH*TAN(DEL)
      THTS=ACOS(COTHTS)/RADFAC
      TH=MIN(THTS,THSS)
      SO=1.356*(1.+.0167*COS(IDAY*ANFAC))**2
      SOH=SO*HRFAC*(COSLAT*COS(DEL)*SIN(THSS*RADFAC)+THSS*RADFAC*SINLA
     +SINDEL)
      SH=DAYKH*SOH
C***********************************************************************
C         FUNCTION DKD CALCULATES A DAILY KD VALUE USING THE
C         DAILY KH VALUE BY THE METHOD DESCRIBED ON PAGE 11-13
C         OF "PHOTOVOLTAIC STAND ALONE SYSTEMS"
C***********************************************************************
      DAYKD=DKD(DAYKH)
      RD=XFACT*(SIN(TH*RADFAC)-TH*RADFAC*COS(THTS*RADFAC))/(SIN(THSS*R
     +FAC)-THSS*RADFAC*COS(THSS*RADFAC))
      DAYINS=SH*((1.-DAYKD)*RD+.5*(1.+COSPHI)*DAYKD+.5*(1.-COSPHI)*RHO
      WRITE (8,*) IDAY,DAYINS,SOH,SH
      DAYLGT=2.*TH/15.
      B=SQRTPI*DAYLGT
      ISTRT=IFIX(12.-DAYLGT/2.)+1
      IEND=IFIX(12.+DAYLGT/2.)
      PITD=SQPI/DAYLGT
      SUM=0.
      DO 20 IHR=ISTRT,IEND
      ARG=-(((DAYLGT/2.-ABS(12-IHR))/B)**2)
      HRINS(IHR)=DAYINS*PITD*(1.-EXP(ARG))
   20 SUM=SUM+HRINS(IHR)
      IE=ISTRT-1
      DO 30 IHR=1,IE
   30 HRINS(IHR)=0.
      IB=IEND+1
      DO 40 IHR=IB,24
   40 HRINS(IHR)=0.
      CORR=DAYINS/SUM
      DO 50 IHR=ISTRT,IEND
   50 HRINS(IHR)=HRINS(IHR)*CORR
   60 WRITE (7,150) IDAY,HRINS
      CALL USHV1 (8HHISTOGRM,TAB,10,IOPT,A,W,IW,IER)
      STOP
   70 FORMAT (' DO YOU WANT TO CHANGE THE RANDOM SEED? (1=YES,0=NO)')
   80 FORMAT (' ENTER SEED')
```

```
 90 FORMAT (' ENTER 12 CLEARNESS INDEXES ')
100 FORMAT (' LATITUDE (DEGREES) ?')
110 FORMAT (' GROUND REFLECTANCE RHO ?')
120 FORMAT (' ARRAY TILT ANGLE ?')
130 FORMAT (17X,'BETA PRMTRS'/7X,'JUL CLRN. -----------'/1X,'MONTH DAY
  +  IND    P     Q'/1X,'----- --- ----- ----- -----')
140 FORMAT (2X,I2,3X,I3,1X,F5.3,1X,2(F5.2,1X))
150 FORMAT (1X,I3,24(1X,F4.2))
    END
```

```
C***********************************************************************
C         SUBROUTINE TO COMPUTE A PP AND A QQ VALUE FOR A GIVEN KH     *
C***********************************************************************
      SUBROUTINE PQ (XKH,PP,QQ)
      DIMENSION
     +    P(5),          Q(5),          XK(5)
      DATA
     +    P /1.131,1.496,2.491,3.182,14.32/,
     +    Q /2.627,2.176,2.408,2.038,5.906/,
     +    XK /.3,.4,.5,.6,.7/
      IF (XKH.GT.0.3) GO TO 10
      PP=P(1)
      QQ=Q(1)
      RETURN
   10 IF (XKH.LT.0.7) GO TO 20
      PP=P(5)
      QQ=Q(5)
      RETURN
   20 IND=IFIX((XKH-.3)/.4*4.)+1
      PP=P(IND)+(P(IND+1)-P(IND))*(XKH-XK(IND))*10.
      QQ=Q(IND)+(Q(IND+1)-Q(IND))*(XKH-XK(IND))*10.
      RETURN
      END


C***********************************************************************
C         PROGRAM TO COMPUTE A DAILY DIFFUSE INSOLATION FACTOR         *
C         AS A FUNCTION OF CLEARNESS INDEX KH , USING THE METHOD       *
C         GIVEN IN "PHOTOVOLTAIC STAND ALONE SYSTEMS", PAGE 11-13.     *
C***********************************************************************
      FUNCTION DKD (DAYKH)
      IF (DAYKH.GT.0.1557) GO TO 10
      DKD=.99
      RETURN
   10 IF (DAYKH.LT.0.761) GO TO 20
      DKD=.2255
      RETURN
   20 DKD=1.188-DAYKH*(2.272-DAYKH*(9.473-DAYKH*(21.856-14.648*DAYKH)))
      RETURN
      END
```

PROGRAM LISTINGS

HOURLY WINDSPEED GENERATOR

```
C***********************************************************************
C        PROGRAM TO GENERATE HOURLY RANDOM WIND VELOCITIES            *
C        FOR 365 DAYS USING WEIBULL DISTRIBUTION                      *
C***********************************************************************
      DIMENSION
     +     A(72),          AVGDAY(365),    AVGV(13),       FACT(3),
     +     FACTOR(365),    IOPT(5),        IT(24),         IW(132),
     +     NDAYS(12),      RAND(1),        SUMHR(24),      SUMWK(52),
     +     TAB1(10),       V(24),          VM(24),         W(132),
     +     WIND(24),       WSPD(24)
      DOUBLE PRECISION
     +     DSEED
      DATA
     +     FACT /1.05,.94,.83/,
     +     IOPT /0,1,0,0,1/,
     +     NDAYS /31,28,31,30,31,30,31,31,30,31,30,31/
      CALL UGETIO (2,5,6)
      DSEED=170247.
      WRITE (6,200)
      READ (5,*) ISDEC
      IF (ISDEC.EQ.1) WRITE (6,210)
      IF (ISDEC.EQ.1) READ (5,*) DSEED
C***********************************************************************
C        INITIALIZE HOURLY (SUMHR) AND WEEKLY (SUMWK) WIND SPEED      *
C        TOTALS TO BE USED FOR COMPUTING AVERAGES                     *
C***********************************************************************
      DO 10 I=1,24
   10 SUMHR(I)=0.
      DO 20 I=1,52
   20 SUMWK(I)=0.
C***********************************************************************
C        READ IN THE NUMBER OF AVAILABLE MEAN WIND VELOCITY           *
C        VALUES (N)                                                   *
C***********************************************************************
      WRITE (6,220)
      READ (5,*) N
C***********************************************************************
C        READ IN N PAIRS OF TIME(IT) VS. MEAN WIND VELOCITY (V) DATA  *
C***********************************************************************
      WRITE (6,230)
      DO 30 I=1,N
   30 READ (5,*) IT(I),V(I)
C***********************************************************************
C        GENERATE 24 HOURLY MEAN WIND VELOCITIES BY LINEAR            *
C        INTERPOLATION FROM MEAN WIND VELOCITY VALUES READ IN ABOVE   *
C***********************************************************************
      IF (N.EQ.1) GO TO 80
      IDT=(24-IT(N))+IT(1)
      DV=-(V(N)-V(1))
      DDV=DV/IDT
      IF (IT(N).EQ.24) VM(24)=V(N)
      IF (IT(N).EQ.24) GO TO 50
      IBEG=IT(N)+1
      IEND=24
```

```
      DO 40 J=IBEG,IEND
   40 VM(J)=V(N)+(J-IBEG+1)*DDV
   50 IBEG=1
      IEND=IT(1)
      DO 60 J=IBEG,IEND
   60 VM(J)=VM(24)+J*DDV
      DO 70 I=2,N
      IDT=IT(I)-IT(I-1)
      DV=V(I)-V(I-1)
      DDV=DV/IDT
      IBEG=IT(I-1)+1
      IEND=IT(I)
      DO 70 J=IBEG,IEND
   70 VM(J)=V(I-1)+(J-IBEG+1)*DDV
      GO TO 100
   80 DO 90 J=1,24
   90 VM(J)=V(1)
  100 SUM=0.
      DO 110 J=1,24
  110 SUM=SUM+VM(J)
      AVGWIN=SUM/24.
      DO 120 J=1,2
      IB=(J-1)*12+1
      IE=IB+11
  120 WRITE (6,240) (VM(K),K=IB,IE)
C*******************************************************************
C        READ IN 12 MONTHLY MEAN WIND SPEEDS
C*******************************************************************
      WRITE (6,250)
      READ (5,*) (AVGV(K),K=1,12)
C*******************************************************************
C        GENERATE 365 DAILY MEAN WIND SPEEDS FROM MONTHLY
C        MEAN VALUES BY LINEAR INTERPOLATION
C*******************************************************************
      IDAY=1
      AVGV(13)=AVGV(1)
      DO 130 IMON=1,12
      LIM=NDAYS(IMON)
      DELT=(AVGV(IMON+1)-AVGV(IMON))/LIM
      DO 130 IDD=1,LIM
      AVGDAY(IDAY)=AVGV(IMON)+(IDD-1)*DELT
      FACTOR(IDAY)=AVGDAY(IDAY)/AVGWIN
  130 IDAY=IDAY+1
      WRITE (6,260)
      READ (5,*) IVR
      VARB=FACT(IVR)
      AMAX=-1.E+10
      AMIN=1.E+10
C*******************************************************************
C        GENERATE 24 RANDOM WIND VELOCITY VALUES FOR 365 DAYS
C*******************************************************************
      DO 150 IDAY=1,365
      WRITE (11,*) IDAY,AVGDAY(IDAY),FACTOR(IDAY)
      SUM=0.
```

```
C***********************************************************************
C        THE METHOD USED HERE IS FROM "A. MIKHAIL (1981). WIND POWER   *
C        FOR DEVELOPING NATIONS. SOLAR ENERGY RESEARCH INSTITUTE REPORT*
C        NO:DE 81 025792, JULY 1981"                                   *
C***********************************************************************
      DO 140 IHR=1,24
      WAVG=VM(IHR)*FACTOR(IDAY)
      IF (WAVG.LT.0.) WAVG=0.
      C=VARB*SQRT(WAVG)
      X=1.+(1./C)
      IF (X.GT.25.) WRITE (6,*) IDAY,IHR,X
      IF (X.GT.25.) X=25.
      G=WAVG/GAMMA(X)
C***********************************************************************
C        GGWIB IS AN IMSL SUBROUTINE TO GENERATE WEIBULL RANDOM        *
C        DEVIATE (RAND)                                                *
C***********************************************************************
      CALL GGWIB (DSEED,C,1,RAND)
      WSPD(IHR)=RAND(1)*G
      IF (WSPD(IHR).LT.0.) WSPD(IHR)=0.
      IF (WSPD(IHR).GT.AMAX) AMAX=WSPD(IHR)
      IF (WSPD(IHR).LT.AMIN) AMIN=WSPD(IHR)
      SUM=SUM+WSPD(IHR)
      SUMHR(IHR)=SUMHR(IHR)+WSPD(IHR)
  140 CONTINUE
      DAVG=SUM/24.
      ID=(IDAY-1)/7+1
      IF (ID.GT.52) GO TO 150
      SUMWK(ID)=SUMWK(ID)+DAVG
      WRITE (8,*) IDAY,DAVG
  150 WRITE (7,270) IDAY,(WSPD(I),I=1,24)
      ENDFILE 7
      REWIND 7
C***********************************************************************
C        PREPARE DATA FILES FOR PLOTTING HOURLY AND WEEKLY WIND SPEED  *
C        AVERAGES AND THE HISTOGRAM OF THE GENERATED DATA              *
C***********************************************************************
      DO 160 I=1,24
      SUMHR(I)=SUMHR(I)/365.
  160 WRITE (9,*) I,SUMHR(I)
      DO 170 I=1,52
      SUMWK(I)=SUMWK(I)/7.
  170 WRITE (10,*) I,SUMWK(I)
      NCLASS=10
      DO 180 I=1,NCLASS
  180 TAB1(I)=0.
      DO 190 I=1,365
      READ (7,*) IDAY,WIND
      DO 190 J=1,24
      INDEX=IFIX((WIND(J)-AMIN)/(AMAX-AMIN)*NCLASS)+1
      IF (INDEX.LT.1) INDEX=1
      IF (INDEX.GT.NCLASS) INDEX=NCLASS
      TAB1(INDEX)=TAB1(INDEX)+1
  190 CONTINUE
```

```
      WRITE (6,280) AMIN,AMAX,TAB1
C***************************************************************************
C        USHV1 IS AN IMSL ROUTINE TO PLOT A HISTOGRAM OF FREQUENCIES      *
C        STORED IN TAB1                                                    *
C***************************************************************************
      CALL USHV1 (8HHISTOGRM,TAB1,10,IOPT,A,W,IW,IER)
      STOP 'NORMAL EXIT'
  200 FORMAT (' DO YOU WANT TO CHANGE THE RANDOM SEED? (1=YES,0=NO)')
  210 FORMAT (' ENTER SEED')
  220 FORMAT (' # OF AVAILABLE HOURLY MEAN VALUES ?')
  230 FORMAT (' ENTER TIME AND CORRESPONDING MEAN WIND SPD (M/SEC)')
  240 FORMAT (1X,12(F5.2,2X))
  250 FORMAT (' ENTER 12 MONTHLY MEAN WIND SPEEDS')
  260 FORMAT (' ENTER VARIABILITY (1,2 OR 3) ')
  270 FORMAT (1X,I3,24(1X,F4.1))
  280 FORMAT (' MIN=',F7.3/' MAX=',F7.3/10(1X,F7.0))
      END
```

PROGRAM LISTING

PV/WIND HYBRID SYSTEM SIZING,
COSTING AND PERFORMANCE SIMULATION MODEL

```
C***********************************************************************
C        PROGRAM TO SIZE A PV+WIND SYSTEM.                             *
C        SOLAR RADIATION DATA (SUN) ARE READ FROM FILE 7               *
C        WIND SPEED DATA (WIND) ARE READ FROM FILE 8                   *
C        DEMAND PROFILE (DEMAND) IS READ FROM FILE 9                   *
C***********************************************************************
      DIMENSION
     +    BAT(20),        BBC(20),        BOSCST(3),      CC(10),
     +    CE(10),         CEBOS(3),       CEWN(20),       CF(10),
     +    DEMAND(24),     FC(10),         FUEL(10),       HMACC(20),
     +    HRESS(20),      LFBOS(3),       LFTBOS(3),      LFTWN(20),
     +    LFWN(20),       N(10),          NT(10),         OM(10),
     +    OMBOS(3),       OMWN(20),       PR(20),         PVMAX(20),
     +    SUN(24),        VI(20),         VM(20),         VR(20),
     +    WIND(24),       WINDP(24),      WNDCST(20)
      COMMON /WNDMCH/
     +    A,              B,              C,              HMAC,
     +    HRES,           PPR,            VII,            VMM,
     +    VRR
      COMMON /COSTF/
     +    CCM,            CD,             CI,             CITC,
     +    CO,             CP,             CPI,            CT,
     +    LIFE,           LTAX,           RC,             RD,
     +    RP,             XKWH
      REAL
     +    ND
      WRITE (6,110)
      READ (5,120) NBASE
C***********************************************************************
C        READ PV SYSTEM DATA                                           *
C***********************************************************************
      WRITE (6,130)
      READ (5,120) PVEFF,PVCOST,OMPV,LFPV,LFTPV,CEPV
C***********************************************************************
C        READ BATTERY DATA                                             *
C***********************************************************************
      WRITE (6,140)
      READ (5,120) DCOEF,CCOEF,DDISCH,BATDPT,ETAB,BATCST,OMBAT,LFBAT,LFT
     +BAT,CEBAT,ND,EFINV
      WRITE (6,150)
      READ (5,120) NW,DRT
C***********************************************************************
C        READ THE NUMBER OF WIND SYSTEMS TO BE CONSIDERED (NW)         *
C        AND READ THE DATA FOR EACH SYSTEM.                            *
C***********************************************************************
      WRITE (6,160) NW
      DO 10 I=1,NW
   10 READ (5,120) PR(I),VI(I),VR(I),VM(I),WNDCST(I),OMWN(I),HRESS(I),HM
     +ACC(I),LFWN(I),LFTWN(I),CEWN(I)
C***********************************************************************
C        READ BALANCE OF SYSTEM COST COMPONENTS FOR EACH UNIT (PV,     *
C        WIND, AND BATTERIES)                                          *
C***********************************************************************
      WRITE (6,170)
```

```
      DO 20 I=1,3
   20 READ (5,120) BOSCST(I),OMBOS(I),LFBOS(I),LFTBOS(I),CEBOS(I)
C*********************************************************************
C         READ FINANCIAL PARAMETERS                                  *
C*********************************************************************
      WRITE (6,180)
      READ (5,120) RD,CD,RP,CP,RC,CCM,CI,CO,CT,CPI,CITC
C*********************************************************************
C         READ SYSTEM LIFE (LIFE) AND TAX LIFE (LTAX)                *
C*********************************************************************
      WRITE (6,190)
      READ (5,120) LIFE,LTAX
C*********************************************************************
C         INITIALIZE                                                 *
C*********************************************************************
      DO 30 I=1,7
      CF(I)=0.
      FC(I)=0.
      FUEL(I)=0.
      CC(I)=0.
      OM(I)=0.
      N(I)=LIFE
      NT(I)=LTAX
   30 CE(I)=0.
      WRITE (6,200)
C*********************************************************************
C         SIZE SYSTEM COMPONENTS AND SIMULATE SYSTEM PERFORMANCE FOR *
C         EACH WIND MACHINE AVAILABLE.                               *
C*********************************************************************
      DO 80 I=1,NW
      HRES=HRESS(I)
      HMAC=HMACC(I)
      REWIND 7
      REWIND 8
      REWIND 9
C*********************************************************************
C         COMPUTE WIND MACHINE PERFORMANCE PARAMETERS (A, B, AND C)
C*********************************************************************
      PPR=PR(I)
      VMED=(VI(I)+VR(I))/2.
      VII=VI(I)
      VRR=VR(I)
      VMM=VM(I)
      B=PR(I)*(((VMED/VR(I))**3)*(VR(I)**2-VI(I)**2)-(VMED**2-VI(I)**2)
     +/((VR(I)-VI(I))*(VR(I)-VMED)*(VMED-VI(I)))
      C=(PR(I)-B*(VR(I)-VI(I)))/(VR(I)**2-VI(I)**2)
      A=-B*VI(I)-C*VI(I)**2
      PVMAX(I)=0.
      BAT(I)=0.
      NPRIOD=365/NBASE
      SUMKH=0.
C*********************************************************************
C         SIZE THE SYSTEM COMPONENTS FOR THE PERIOD BEING CONSIDERED.  *
C         THIS PORTION OF THE PROGRAM SIZES THE PV ARRAY ONLY.         *
```

```
C •        ARRAY SIZE FOR A GIVEN PERIOD IS PVSIZ.                          *
C         THE LARGEST PVSIZ VALUE IS THE FINAL ARRAY SIZE (PVMAX).          *
C***********************************************************************
      DO 50 JJ=1,NPRIOD
      SUMSUN=0.
      SUMWIN=0.
      SUMDEM=0.
      DO 40 J=1,NBASE
      READ (7,210) SUN
      READ (8,210) WIND
      READ (9,210) DEMAND
      DO 40 K=1,24
      W=WIND(K)
      SUMSUN=SUMSUN+SUN(K)
      WINDP(K)=PWIND(W)*DRT
      SUMWIN=SUMWIN+WINDP(K)
   40 SUMDEM=SUMDEM+DEMAND(K)
      SUMDEM=SUMDEM/EFINV
      SUMKH=SUMKH+SUMDEM
      DIFF=SUMDEM-SUMWIN
      PVSIZ=(DIFF/SUMSUN)/PVEFF
      IF (PVSIZ.GT.PVMAX(I)) IDD=JJ
      IF (PVSIZ.GT.PVMAX(I)) PVMAX(I)=PVSIZ
C             WRITE (11,210) JJ,SUMDEM,SUMWIN,SUMSUN,DIFF,PVSIZ,PVMAX(I)
   50 CONTINUE
      XKWH=SUMKH
      REWIND 7
      REWIND 8
      REWIND 9
      ENGM=1.E+6
      SMNEG=1.E+6
      SDMSTO=0.
C***********************************************************************
C         START FROM THE BEGINNING OF THE SIMULATION PERIOD AND         *
C         DETERMINE THE BATTERY SIZE (BAT) REQUIRED FOR THE PV ARRAY    *
C         SIZE COMPUTED ABOVE AND THE WIND MACHINE UNDER CONSIDERATION  *
C***********************************************************************
      DO 70 JJ=1,365
      READ (7,210) SUN
      READ (8,210) WIND
      READ (9,210) DEMAND
      POSDIF=0.
      ENGDIF=0.
      POSMAX=-1.E+6
      SUMDEM=0.
      DO 60 K=1,24
      W=WIND(K)
      WINDP(K)=PWIND(W)*DRT
      SUMDEM=SUMDEM+DEMAND(K)
      DIFF=(PVMAX(I)*PVEFF*SUN(K)+WINDP(K))-DEMAND(K)/EFINV
      IF (DIFF.GT.0.) GO TO 60
      ENGDIF=ENGDIF+DIFF
      IF (DIFF.LT.SMNEG) SMNEG=DIFF
   60 CONTINUE
```

```
      SUMDEM=SUMDEM/EFINV
      IF (ENGDIF.LT.ENGM) SDMSTO=SUMDEM
      IF (ENGDIF.LT.ENGM) ENGM=ENGDIF
   70 CONTINUE
      BAT(I)=ABS(ENGM)/(ETAB*DDISCH)
      BAT1=ABS(SMNEG)/DCOEF
      BAT(I)=ND*MAX(BAT(I),BAT1)
      PVKWP=PVMAX(I)*PVEFF
      CC(1)=PVCOST*PVKWP
      CC(2)=WNDCST(I)
      CC(3)=BATCST*BAT(I)
      CC(4)=BOSCST(1)*PVKWP
      CC(5)=BOSCST(2)*PR(I)
      CC(6)=BOSCST(3)
      OM(1)=CC(1)*OMPV
      OM(2)=CC(2)*OMWN(I)
      OM(3)=BAT(I)*OMBAT
      OM(4)=OMBOS(1)*CC(4)
      OM(5)=OMBOS(2)*CC(5)
      OM(6)=OMBOS(3)
      N(1)=LFPV
      NT(1)=LFTPV
      N(2)=LFWN(I)
      NT(2)=LFTWN(I)
      N(3)=LFBAT
      NT(3)=LFTBAT
      N(4)=LFBOS(1)
      N(5)=LFBOS(2)
      N(6)=LFBOS(3)
      NT(4)=LFTBOS(1)
      NT(5)=LFTBOS(2)
      NT(6)=LFTBOS(3)
      CE(1)=CEPV
      CE(2)=CEWN(I)
      CE(3)=CEBAT
      CE(4)=CEBOS(1)
      CE(5)=CEBOS(2)
      CE(6)=CEBOS(3)
C*********************************************************************
C         DETERMINE SYSTEM COST COMPONENTS
C*********************************************************************
      CALL COST (IND,CC,OM,FUEL,N,NT,CF,CE,FC,BBCC)
      BBC(I)=BBCC*EFINV
      CINIT=CC(1)+CC(2)+CC(3)+CC(4)+CC(5)+CC(6)
      WRITE (6,220) I,PR(I),PVMAX(I),BAT(I),BBC(I),CINIT
   80 CONTINUE
C*********************************************************************
C         SIMULATE SYSTEM PERFORMANCE FOR THE SPECIFIED COMBINATION
C         (IF ANY)
C*********************************************************************
      WRITE (6,230)
      WRITE (6,240)
      READ (5,120) IDESIM
      IF (IDESIM.EQ.0) GO TO 100
```

```
 90 WRITE (6,250)
    READ (5,120) IS
    IF (IS.EQ.0) GO TO 100
    CALL SIMULA (BAT(IS),BATDPT,ETAB,PVMAX(IS),PVEFF,PR(IS),VI(IS),VR(
   +IS),VM(IS),DCOEF,CCOEF,DDISCH,HRESS(IS),HMACC(IS),DRT,EFINV)
    GO TO 90
100 STOP 'END!'
110 FORMAT (' ENTER TIME BASE FOR P/V SIZING')
120 FORMAT ()
130 FORMAT (' ENTER PVEFF,PVCOST/KW,OMPV,LFPV,LFTPV,CEPV')
140 FORMAT (' ENTER DCOEF,CCOEF,DDISCH,BATDPT,ETAB,COST/KW,OMBAT,LFBAT
   +,LFTBAT',',CEBAT,ND,EFINV')
150 FORMAT (' ENTER # OF WIND SYSTEMS, DERATING FRACTION')
160 FORMAT (' ENTER ',I2,' LINES OF PR,VI,VR,VM,COST,O&M,MES.HGT,','HU
   +B HGT,LFWN,LFTWN,CEWN')
170 FORMAT (' ENTER 3 LINES OF BOSCST,OMBOS,LFBOS,LFTBOS,CEBOS')
180 FORMAT (' ENTER RD, CD, RP, CP, RC, CCM, CI, CO, CT, CPI, CITC')
190 FORMAT (' ENTER PROJECT LIFE, TAX LIFE')
200 FORMAT (////13X,'WIND',7X,'PV'/'  SYSTEM    MACHINE    ARRAY',4X,'B
   +ATTERY  LEVELIZED  INITIAL'/'  NUMBER',5X,3('SIZE',6X),'COST',6X,'
   +COST'/13X,'(KW)',5X,'(SQ','.M)',4X,'(KWH)',4X,'($/KWH)',5X,'($)'/1
   +X,8('-'),5(1X,9('-')))
210 FORMAT (4X,24(1X,F4.2))
220 FORMAT (4X,I3,3X,5(E9.4,1X))
230 FORMAT (1X,59('-'))
240 FORMAT (////' SIMULATION ? (1=YES, 0=NO)')
250 FORMAT (////' WHICH SYSTEM?')
    END
```

```
C*********************************************************************
C        FUNCTION SUBPROGRAM TO COMPUTE THE ENERGY GENERATED BY A
C        WIND MACHINE (PWIND), GIVEN AN AVERAGE HOURLY WIND SPEED
C        (WIND).
C*********************************************************************
      FUNCTION PWIND (WIND)
      COMMON /WNDMCH/
     +    A,              B,              C,              HMAC,
     +    HMES,           PRR,            VII,            VMM,
     +    VRR
      W=WIND
      RAT=HMAC/HMES
      IF (ABS(RAT-1.).GT.1.E-6) W=WIND*(RAT**.142857)
      IF (W.GT.VMM.OR.W.LT.VII) GO TO 10
      IF (W.GT.VRR) PWIND=PRR
      IF (W.LT.VRR) PWIND=A+B*W+C*W*W
      GO TO 20
   10 PWIND=0.
   20 RETURN
      END
```

```
C****************************************************************************
C        PROGRAM TO COMPUTE VARIOUS SYSTEM COST COMPONENTS                  *
C****************************************************************************
      SUBROUTINE COST (IND,CC,OM,FUEL,FMIN,N,NT,CF,CE,FC,BBC)
      DIMENSION
     +    AAD(10),       AIT(10),       AITC(10),      ATD(10),
     +    CC(10),        CE(10),        CF(10),        CIR(10),
     +    CRF(10),       FC(10),        FCR(10),       FLF(10),
     +    FUEL(10),      N(10),         NR(10),        NT(10),
     +    OM(10),        PWF(10),       PWFT(10),      RF(10)
      COMMON /COSTF/
     +    CCM,           CD,            CI,            CITC,
     +    CO,            CP,            CPI,           CT,
     +    LIFE,          LTAX,          NBKUP,         RC,
     +    RD,            RP,            XKWH
      IND=1
      ITST=1
      M=7
      IF (IND.EQ.0) GO TO 20
      CD=(1+CD)/(1+CI)-1.
      CP=(1+CP)/(1+CI)-1.
      CCM=(1+CCM)/(1+CI)-1.
      CO=(1+CO)/(1+CI)-1.
      DO 10 I=1,M
      CF(I)=(1+CF(I))/(1+CI)-1.
   10 CE(I)=(1+CE(I))/(1+CI)-1.
      CI=0.
   20 R=RD*CD+RP*CP+RC*CCM
      LIM=M+1
      N(LIM)=LIFE
      NT(LIM)=LTAX
      DO 60 I=1,LIM
      CRF(I)=R/(1.-(1.+R)**(-N(I)))
      PWF(I)=1./CRF(I)
      AIT(I)=(CRF(I)-1./N(I))*(1.-(RD*CD/R))*(CT/(1.-CT))
      IF (N(I).EQ.NT(I)) GO TO 30
      PWFT(I)=(1.-(1.+R)**(-NT(I)))/R
      GO TO 40
   30 PWFT(I)=PWF(I)
   40 ATD(I)=2.*CRF(LIM)*(NT(I)-PWFT(I))/(NT(I)*(NT(I)+1.)*R)
      IF (ITST.EQ.0) GO TO 50
      AAD(I)=(ATD(I)-1./N(I))*(CT/(1.-CT))
      AITC(I)=CRF(I)*CITC/((1.+R)*(1.-CT))
      GO TO 60
   50 AAD(I)=(ATD(I)-1./N(I))*(1.-CT*RD*CD/R)*(CT/(1.-CT))
      AITC(I)=(CITC/(1.-CT))*(CRF(I)/(1.+R)-CT*RD*CD*(CRF(I)/(1+R)-1./N(
     +I))/R)
   60 FCR(I)=CRF(I)+AIT(I)-AAD(I)-AITC(I)+CPI
      DO 100 I=1,M
      IF (N(I).LT.LIFE) GO TO 70
      CIR(I)=1.
      GO TO 90
   70 A=LIFE
      B=N(I)
```

```
      NR(I)=A/B
      IF ((LIFE/N(I))*N(I).EQ.LIFE) NR(I)=NR(I)-1
      SUM=0.
      IUP=NR(I)
      DO 80 J=1,IUP
  80  SUM=SUM+(1.+CE(I))/(1.+R)**(J*N(I))
      CIR(I)=(CRF(LIM)/CRF(I))*(FCR(I)/FCR(LIM))*(1.+SUM)
  90  RF(I)=(1.+CF(I))/(1.+R)
      FLF(I)=CRF(LIM)*(RF(I)*(1.-RF(I)**LIFE)/(1.-RF(I)))
 100  CONTINUE
      EF=(1.+CO)/(1.+R)
      VOM=CRF(M+1)*(EF*(1.-EF**LIFE)/(1.-EF))
      SUM1=NBKUP*CC(2)
      COML=0.
      FCL=0.
      DO 110 I=1,M
      SUM1=SUM1+CC(I)*CIR(I)
      COML=COML+OM(I)
 110  FCL=FCL+(FUEL(I)+FMIN)*FC(I)*FLF(I)
      COML=COML*VOM
      ECC=FCR(LIM)*SUM1
      TTLC=ECC+COML+FCL
      BBC=TTLC/XKWH
      RETURN
      END
```

```
C***********************************************************************
C        SUBROUTINE TO SIMULATE THE PV+WIND SYSTEM PERFORMANCE         *
C***********************************************************************
      SUBROUTINE SIMULA (BATSIZ,BATDPT,ETA,PVSIZ,PVEFF,WNDSZ,VI,VR,VM,DC
     +OEF,CCOEF,DDISCH,HMES,HMAC,DRT,EFINV)
      DIMENSION
     +    DEMAND(24),     SUN(24),        WIND(24)
      COMMON /WNDMCH/
     +    A,              B,              C,              HMACC,
     +    HMESS,          PRR,            VII,            VMM,
     +    VRR
      HMACC=HMAC
      HMESS=HMES
      VII=VI
      VRR=VR
      VMM=VM
      PRR=WNDSZ
      BATCHG=BATSIZ*BATDPT/100.
      VMED=(VI+VR)/2.
      B=PRR*(((VMED/VR)**3)*(VR**2-VI**2)-(VMED**2-VI**2))/((VR-VI)*(VR-
     +VMED)*(VMED-VI))
      C=(PRR-B*(VR-VI))/(VR**2-VI**2)
      A=-B*VI-C*VI**2
      DISLIM=DCOEF*BATSIZ
      CHGLIM=CCOEF*BATSIZ
      BATLL=(1.-DDISCH)*BATSIZ
      REWIND 7
      REWIND 8
      REWIND 9
      TOTDEM=0.
      TOTDEF=0.
      TOTWIN=0.
      TOTPV=0.
      TOTDUM=0.
      KNT=0
      REWIND 10
      DO 50 I=1,365
      READ (7,60) SUN
      READ (8,60) WIND
      READ (9,60) DEMAND
      SUMPV=0.
      SUMWIN=0.
      SUMDSC=0.
      SUMCHG=0.
      SUMDEM=0.
      SUMDUM=0.
      SUMDEF=0.
      DO 40 K=1,24
      PV=SUN(K)*PVSIZ*PVEFF
      WINDP=PWIND(WIND(K))*DRT
      SUMPV=SUMPV+PV
      SUMWIN=SUMWIN+WINDP
      SUMDEM=SUMDEM+DEMAND(K)
      DIFF=PV+WINDP-DEMAND(K)/EFINV
```

```
      IF (DIFF.LT.0.) GO TO 20
C*************************************************************************
C        PROGRAM COMES HERE WHEN ENERGY IS AVAILABLE FOR BATTERY
C        CHARGING,
C*************************************************************************
      CHRG=DIFF
C*************************************************************************
C        RATE OF CHARGING CAN NOT EXCEED CHGLIM. ENERGY IN EXCESS        *
C        OF CHGLIM IS DUMPED.                                            *
C*************************************************************************
      IF (CHRG.LT.CHGLIM) GO TO 10
      DUMP=CHRG-CHGLIM
      CHRG=CHGLIM
      SUMDUM=SUMDUM+DUMP
   10 BATCHG=BATCHG+CHRG*ETA
      SUMCHG=SUMCHG+CHRG*ETA
C*************************************************************************
C        AMOUNT OF CHARGE STORED CAN NOT EXCEED BATTERY CAPACITY.        *
C        ENERGY IN EXCESS OF BATSIZ IS DUMPED.                           *
C*************************************************************************
      IF (BATCHG.LT.BATSIZ) GO TO 40
      DUMP=BATCHG-BATSIZ
      BATCHG=BATSIZ
      SUMDUM=SUMDUM+DUMP
      GO TO 40
C*************************************************************************
C        PROGRAM COMES HERE WHEN BATTERIES SUPPLY ENERGY TO MEET         *
C        THE DEMAND.                                                     *
C*************************************************************************
   20 DSCH=ABS(DIFF)
C*************************************************************************
C        BATTERIES CAN NOT DISCHARGE AT A RATE FASTER THAN DISLIM        *
C        AND BATTERY CHARGE CAN NOT GO BELOW BATLL.                      *
C        COUNT THE NUMBER OF TIMES THIS CONDITION BECOMES LIMITING       *
C        AMOUNT OF DISCHARGE FROM THE BATTERIES IS DSCH.                 *
C*************************************************************************
      IF (DSCH.GT.DISLIM.OR.(BATCHG-DSCH).LT.BATLL) KNT=KNT+1
      IF (DSCH.LT.DISLIM) GO TO 30
C*************************************************************************
C        DEF IS THAT PORTION OF THE DEMAND WHICH CAN NOT BE              *
C        SATISFIED BY THE SYSTEM.                                        *
C*************************************************************************
      DEF=DSCH-DISLIM
      DSCH=DISLIM
      SUMDEF=SUMDEF+DEF
   30 BATCHG=BATCHG-DSCH
      SUMDSC=SUMDSC+DSCH
      IF (BATCHG.GT.BATLL) GO TO 40
      DEF=BATLL-BATCHG
      SUMDEF=SUMDEF+DEF
      BATCHG=BATLL
   40 CONTINUE
      IF (BATSIZ.GT.0.) BATDPT=(BATCHG/BATSIZ)*100.
      TOTDEM=TOTDEM+SUMDEM
```

```
      TOTDEF=TOTDEF+SUMDEF
      TOTPV=TOTPV+SUMPV
      TOTWIN=TOTWIN+SUMWIN
      TOTDUM=TOTDUM+SUMDUM
      WRITE (10,70) I,SUMPV,SUMWIN,BATDPT,SUMCHG,SUMDSC,SUMDEM,SUMDUM,SU
     +MDEF
   50 CONTINUE
      TOTDEM=TOTDEM/EFINV
      PCTDEM=((TOTDEM-TOTDEF)/TOTDEM)*100.
      PCTTIM=((8760.-KNT)/8760.)*100.
      TOTGEN=TOTPV+TOTWIN
      PTDUM=TOTDUM/TOTDEM*100.
      PTDEF=TOTDEF/TOTDEM*100.
      ENDFILE 10
      TOTDEM=TOTDEM*EFINV
      WRITE (6,80) TOTPV
      WRITE (6,90) TOTWIN
      WRITE (6,100) TOTGEN
      WRITE (6,110) TOTDEM
      WRITE (6,120) TOTDUM,PTDUM
      WRITE (6,130) TOTDEF,PTDEF
      WRITE (6,140) PCTDEM
      WRITE (6,150) PCTTIM
      RETURN
   60 FORMAT (4X,24(1X,F4.2))
   70 FORMAT (I3,8(1X,E8.3))
   80 FORMAT (////' TOTAL ENERGY GENERATED'/20X,'PV =',E11.5,' KWH')
   90 FORMAT (18X,'WIND ='E11.5,' KWH')
  100 FORMAT (17X,'TOTAL =',E11.5,' KWH')
  110 FORMAT (/10X,'TOTAL DEMAND =',E11.5,' KWH')
  120 FORMAT ('  TOTAL ENERGY SURPLUS =',E11.5,' KWH (',F5.1,'% OF DEMAN
     +D)')
  130 FORMAT ('  TOTAL ENERGY DEFICIT =',E11.5,' KWH (',F5.1,'% OF DEMAN
     +D)')
  140 FORMAT (/10X,'% OF DEMAND SATISFIED = ',F5.1,' %')
  150 FORMAT (' % OF TIME DEMAND WAS SATISFIED = ',F5.1,'%')
      END
```

PROGRAM LISTINGS

PV/ENGINE HYBRID SYSTEM SIZING,
COSTING AND PERFORMANCE SIMULATION MODEL

```
C***********************************************************************
C        PROGRAM TO SIZE A PV+DIESEL SYSTEM                            *
C***********************************************************************
      DIMENSION
     +    BAT(20),        BOSCST(3),      CAPNOM(20),     CC(10),
     +    CE(10),         CEBOS(3),       CED(20),        CF(10),
     +    CMAX(20),       CMIN(20),       CSIZ(20),       DCOST(20),
     +    DEMAND(24),     FC(10),         FMIN(20),       FUEL(10),
     +    LFBOS(3),       LFD(20),        LFTBOS(3),      LFTD(20),
     +    N(10),          NT(10),         OM(10),         OMBOS(3),
     +    OMD(20),        PVMAX(20),      RL(20,5),       RR(5),
     +    SUN(24)
      COMMON /COSTF/
     +    CCM,            CD,             CI,             CITC,
     +    CO,             CP,             CPI,            CT,
     +    LIFE,           LTAX,           NBKUP,          RC,
     +    RD,             RP,             XKWH
      REAL
     +    ND
      WRITE (6,160)
C***********************************************************************
C        READ SYSTEM OPERATION AND INSTALLATION OPTIONS                *
C***********************************************************************
      READ (5,170) SOLLIM,SOLO,IONNPT,IONOPT,IENBUP,NOPV,IBTPK
C***********************************************************************
C        INITIALIZE                                                    *
C***********************************************************************
      DO 10 I=1,7
      CF(I)=0.
      FC(I)=0.
      FUEL(I)=0.
      CC(I)=0.
      OM(I)=0.
   10 CE(I)=0.
      WRITE (6,180)
C***********************************************************************
C        READ DIESEL GENERATOR DATA (NDIS IS THE NUMBER OF GENERATOR   *
C        SIZES AVAILABLE)                                              *
C***********************************************************************
      READ (5,170) NDIS,FC(2),CF(2),IPL,IPS,NBKUP
      WRITE (6,190) NDIS
      DO 20 I=1,NDIS
   20 READ (5,170) CSIZ(I),DCOST(I),OMD(I),LFD(I),LFTD(I),CED(I),CMIN(I)
     +,CMAX(I),CAPNOM(I),(RL(I,II),II=1,5),FMIN(I)
      WRITE (6,200)
      READ (5,170) NDAYS
      NPRIOD=365/NDAYS
C***********************************************************************
C        READ PV SYSTEM DATA                                           *
C***********************************************************************
      WRITE (6,210)
      READ (5,170) PVEFF,PVCOST,OMPV,LFPV,LFTPV,CEPV
C***********************************************************************
C        READ BATTERY DATA                                             *
```

```
C*********************************************************************
      WRITE (6,220)
      READ (5,170) DCOEF,CCOEF,DDISCH,BATDPT,ETAB,BATCST,OMBAT,LFBAT,LFT
     +BAT,CEBAT,ND,EFINV
C*********************************************************************
C         READ BALANCE OF SYSTEM COST FOR EACH COMPONENT (PV, DIESEL,
C         BATTERIES).
C*********************************************************************
      WRITE (6,230)
      DO 30 I=1,3
   30 READ (5,170) BOSCST(I),OMBOS(I),LFBOS(I),LFTBOS(I),CEBOS(I)
      WRITE (6,240)
C*********************************************************************
C         READ FINANCIAL PARAMETERS
C*********************************************************************
      READ (5,170) RD,CD,RP,CP,RC,CCM,CI,CO,CT,CPI,CITC
C*********************************************************************
C         READ SYSTEM LIFE (LIFE) AND TAX LIFE (LTAX)
C*********************************************************************
      WRITE (6,250)
      READ (5,170) LIFE,LTAX
      DO 40 I=1,7
      N(I)=LIFE
   40 NT(I)=LTAX
C*********************************************************************
C         SIZE THE SYSTEM COMPONENTS FOR EACH GENERATOR SIZE AVAILABLE
C*********************************************************************
      WRITE (6,260)
      DO 150 I=1,NDIS
      PVMAX(I)=0.
      REWIND 7
      REWIND 9
      UPLIM=CMAX(I)*CSIZ(I)
      ALOWL=CMIN(I)*CSIZ(I)
C*********************************************************************
C         PV SYSTEM IS SIZED FIRST TO SATISFY THE TOTAL DEMAND DURING
C         THE PERIOD. PV ARRAY SIZE FOR THE PERIOD IS PVSIZ.
C         THE LARGEST OF PVSIZ VALUES COMPUTED FOR EACH PERIOD
C         (PVMAX) IS THE PV ARRAY SIZE.
C*********************************************************************
      DO 80 J=1,NPRIOD
      DEFICT=0.
      SUMSUN=0.
      DO 70 K=1,NDAYS
      READ (7,270) SUN
      READ (9,270) DEMAND
      DO 60 L=1,24
      SUMSUN=SUMSUN+SUN(L)
      IF (SUN(L).GT.SOLLIM) GO TO 50
      IF (IONOPT.EQ.0.AND.DEMAND(L).LT.ALOWL) GO TO 50
      IF (DEMAND(L).LE.UPLIM) GO TO 60
      DEFICT=DEFICT+(DEMAND(L)-UPLIM)
      GO TO 60
   50 DEFICT=DEFICT+DEMAND(L)
```

```
 60 CONTINUE
 70 CONTINUE
    PVSIZ=(DEFICT/SUMSUN)/PVEFF
    IF (NOPV.EQ.1) PVSIZ=0.
    IF (PVSIZ.GT.PVMAX(I)) PVMAX(I)=PVSIZ
 80 CONTINUE
C***********************************************************************
C        PV ARRAY SIZE IS NOW KNOWN. DIESEL GENERATOR SIZE IS ALSO     *
C        KNOWN. NOW SIZE THE BATTERIES.                                *
C***********************************************************************
    REWIND 7
    REWIND 9
    ENGM=1.E+6
    SMNEG=1.E+6
    SDMSTO=0.
    DO 110 JJ=1,365
    READ (7,270) SUN
    READ (9,270) DEMAND
    POSDIF=0.
    ENGDIF=0.
    POSMAX=-1.E+6
    SUMDEM=0.
    DO 100 K=1,24
    IF (SUN(K).GT.SOLLIM) GO TO 90
    IF (IONOPT.EQ.0.AND.DEMAND(K).LT.ALOWL) GO TO 90
    IF (DEMAND(K).LE.UPLIM) DEMAND(K)=0.
    IF (DEMAND(K).GT.UPLIM) DEMAND(K)=DEMAND(K)-UPLIM
 90 SUMDEM=SUMDEM+DEMAND(K)
    DIFF=(PVMAX(I)*PVEFF*SUN(K))-DEMAND(K)
    IF (DIFF.GT.0.) GO TO 100
    ENGDIF=ENGDIF+DIFF
    IF (DIFF.LT.SMNEG) SMNEG=DIFF
100 CONTINUE
    IF (ENGDIF.LT.ENGM) SDMSTO=SUMDEM
    IF (ENGDIF.LT.ENGM) ENGM=ENGDIF
110 CONTINUE
    BAT(I)=ABS(ENGM)/(ETAB*DDISCH)
    BAT1=ABS(SMNEG)/DCOEF
    BAT(I)=ND*MAX(BAT(I),BAT1)
    PVKWP=PVMAX(I)*PVEFF
C***********************************************************************
C        EVERY COMPONENT IS SIZED. SIMULATE SYSTEM PERFORMANCE         *
C***********************************************************************
    DO 120 IIJ=1,5
120 RR(IIJ)=RL(I,IIJ)
    IF (IBTPK.EQ.0) CALL SIMULA (PVMAX(I),CCOEF,DCOEF,PVEFF,ETAB,BATDP
   +T,DDISCH,IENOFF,IONNPT,BAT(I),RR,CSIZ(I),UPLIM,ALOWL,GALS,RUNT,TOT
   +DEM,SOLO,IPL,IPS,PCTTIM,PCTDEM,TOTDIS,TOTDEF,TOTPV,IONOPT,IENBUP)
    IF (IBTPK.EQ.1) CALL SIML1 (PVMAX(I),CCOEF,DCOEF,PVEFF,ETAB,BATDPT
   +,DDISCH,IENOFF,IONNPT,BAT(I),RR,CSIZ(I),UPLIM,ALOWL,GALS,RUNT,TOTD
   +EM,SOLO,IPL,IPS,PCTTIM,PCTDEM,TOTDIS,TOTDEF,TOTPV,IONOPT,IENBUP)
    CC(1)=PVCOST*PVKWP
    CC(2)=DCOST(I)
    CC(3)=BATCST*BAT(I)
```

```
      CC(4)=BOSCST(1)*PVKWP
      CC(5)=BOSCST(2)*CSIZ(I)
      CC(6)=BOSCST(3)
      CCSUM=CC(1)+(1+NBKUP)*CC(2)+CC(3)+CC(4)+CC(5)+CC(6)
      OM(1)=CC(1)*OMPV
      OM(2)=RUNT*OMD(I)
      OM(3)=BAT(I)*OMBAT
      OM(4)=CC(4)*OMBOS(1)
      OM(5)=CC(5)*OMBOS(2)
      OM(6)=OMBOS(3)
      N(1)=LFPV
      NT(1)=LFTPV
      IF (RUNT.GT.0.) GO TO 130
      N(2)=LFD(I)
      NT(2)=LFTD(I)
      GO TO 140
  130 N(2)=(LFD(I)*8760.*CAPNOM(I))/RUNT
      NT(2)=LFTD(I)
  140 N(3)=LFBAT
      NT(3)=LFTBAT
      N(4)=LFBOS(1)
      NT(4)=LFTBOS(1)
      N(5)=LFBOS(2)
      NT(5)=LFTBOS(2)
      N(6)=LFBOS(3)
      NT(6)=LFTBOS(3)
      CE(1)=CEPV
      CE(2)=CED(I)
      CE(3)=CEBAT
      CE(4)=CEBOS(1)
      CE(5)=CEBOS(2)
      CE(6)=CEBOS(3)
      FUEL(2)=GALS
      XKWH=TOTDEM-TOTDEF
C************************************************************************
C          COMPUTE SYSTEM COST COMPONENTS
C************************************************************************
      CALL COST (IND,CC,OM,FUEL,FMIN(I),N,NT,CF,CE,FC,BBC)
      BBC=BBC/EFINV
      GALS=GALS+FMIN(I)
      WRITE (6,280) CSIZ(I),PVMAX(I),BAT(I),TOTDIS,TOTPV,TOTDEM,PCTTI
     +CTDEM,TOTDEF,RUNT,GALS,BBC,CCSUM
  150 CONTINUE
      WRITE (6,290)
      STOP
  160 FORMAT (' ENTER SOLLIM,SOLO,IONNPT,IONOPT,IENBUP,NOPV,IBTPK')
  170 FORMAT ()
  180 FORMAT (' ENTER NDIS,FC,CF,IPL,IPS,NBKUP')
  190 FORMAT (' ENTER ',I2,' LINES OF CSIZ,DCOST,OMD,LFD,LFTD,CED,CMI
     +,'CMAX,CAPNOM,RR(1)...RR(5),FMIN')
  200 FORMAT (' ENTER TIME BASE FOR PV SIZING')
  210 FORMAT (' ENTER PVEFF,PVCOST,OMPV,LFPV,LFTPV,CEPV')
  220 FORMAT (' ENTER DCOEF,CCOEF,DDISCH,BATDPT,ETAB,BATCST,OMBAT,LFB
     +','LFTBAT,CEBAT,ND,EFINV')
```

```
230 FORMAT (' ENTER 3 LINES OF BOSCST,OMBOS,LFBOS,LFTBOS,CEBOS')
240 FORMAT (' ENTER RD,CD,RP,CP,RC,CCM,CI,CO,CT,CPI,CITC')
250 FORMAT (' ENTER LIFE,LTAX')
260 FORMAT (/////' DIES',5X,'PV',6X,'BATTERY   DIESEL',6X,'PV',7X,'TOT
   +AL',4X,'% TIME',4X,'% DEM.',5X,3('TOTAL',5X),'SYSTEM   INITIAL'/'
   +SIZE    SIZE',6X,'SIZE',5X,2('ENERGY',4X),'DEMAND',,3X,'SATSFIED
   +SATSFIED   DEFICIT  RUN TIME  FUEL USED','     COST      COST'/' (KW
   +P)   (M2) ',4(5X,'(KWH)'),25X,'(KWH)',5X,'(HR)',6X,'(GAL)     ($/KW
   +H)    ($)'/,1X,125('-'))
270 FORMAT (4X,24(1X,F4.2))
280 FORMAT (1X,F4.1,12(2X,E8.4))
290 FORMAT (1X,125('-'))
    END
```

```
C*************************************************************************
C        SUBROUTINE TO UPDATE BATTERY STATE OF CHARGE (BATCHG). ENERGY *
C        IN EXCESS OF BATTERY CAPACITY (BATSIZ) IS DUMPED. MAXIMUM     *
C        ACCEPTABLE CHARGE RATE IS "CHGLIM" (CHGLIM=CCOEF*BATSIZ).     *
C        BATTERY EFFICIENCY IS "ETAB" AND AVAILABLE ENERGY FOR CHARGING*
C        IS "CHRG".                                                    *
C*************************************************************************
      SUBROUTINE CHARGE
      COMMON /CHARG/
     +    BATCHG,         BATSIZ,         CHGLIM,         CHRG,
     +    ETAB,           SUMDUM
      IF (CHRG.LT.CHGLIM) GO TO 10
      DUMP=CHRG-CHGLIM
      CHRG=CHGLIM
      SUMDUM=SUMDUM+DUMP
   10 BATCHG=BATCHG+CHRG*ETAB
      IF (BATCHG.LE.BATSIZ) GO TO 20
      DUMP=BATCHG-BATSIZ
      BATCHG=BATSIZ
      SUMDUM=SUMDUM+DUMP
   20 RETURN
      END


C*************************************************************************
C        SUBROUTINE TO COMPUTE FUEL CONSUMPTION AS A FUNCTION OF        *
C        OPERATING LEVEL (OPRTR). FIVE FUEL CONSUMPTION RATES           *
C        CORRESPONDING TO OPERATING LEVELS OF 0, 25, 50, 75, AND 100%   *
C        OF ENGINE CAPACITY ARE ASSUMED TO BE KNOWN. IF ENGINE SIZE     *
C        IS ZERO (I.E. < 1.E-6) FUEL CONSUMPTION IS ZERO.               *
C        FUEL CONSUMPTION RATES BETWEEN TWO KNOWN VALUES ARE            *
C        COMPUTED BY LINEAR INTERPOLATION.
C*************************************************************************
      FUNCTION CONS (DEF)
      COMMON /FUELR/
     +    DR(5),          RR(5),          SIZE
      CONS=0.
      IF (SIZE.LT.1.E-6) RETURN
      OPRTR=DEF/SIZE
      INTRVL=IFIX(OPRTR/.25)+1
      ALOW=(INTRVL-1)*.25
      CONS=(OPRTR-ALOW)*DR(INTRVL)+RR(INTRVL)
      RETURN
      END
```

```
C***************************************************************************
C        PROGRAM TO COMPUTE VARIOUS SYSTEM COST COMPONENTS                 *
C***************************************************************************
      SUBROUTINE COST (IND,CC,OM,FUEL,FMIN,N,NT,CF,CE,FC,BBC)
      DIMENSION
     +    AAD(10),        AIT(10),        AITC(10),       ATD(10),
     +    CC(10),         CE(10),         CF(10),         CIR(10),
     +    CRF(10),        FC(10),         FCR(10),        FLF(10),
     +    FUEL(10),       N(10),          NR(10),         NT(10),
     +    OM(10),         PWF(10),        PWFT(10),       RF(10)
      COMMON /COSTF/
     +    CCM,            CD,             CI,             CITC,
     +    CO,             CP,             CPI,            CT,
     +    LIFE,           LTAX,           NBKUP,          RC,
     +    RD,             RP,             XKWH
      IND=1
      ITST=1
      M=7
      IF (IND.EQ.0) GO TO 20
      CD=(1+CD)/(1+CI)-1.
      CP=(1+CP)/(1+CI)-1.
      CCM=(1+CCM)/(1+CI)-1.
      CO=(1+CO)/(1+CI)-1.
      DO 10 I=1,M
      CF(I)=(1+CF(I))/(1+CI)-1.
   10 CE(I)=(1+CE(I))/(1+CI)-1.
      CI=0.
   20 R=RD*CD+RP*CP+RC*CCM
      LIM=M+1
      N(LIM)=LIFE
      NT(LIM)=LTAX
      DO 60 I=1,LIM
      CRF(I)=R/(1.-(1.+R)**(-N(I)))
      PWF(I)=1./CRF(I)
      AIT(I)=(CRF(I)-1./N(I))*(1.-(RD*CD/R))*(CT/(1.-CT))
      IF (N(I).EQ.NT(I)) GO TO 30
      PWFT(I)=(1.-(1.+R)**(-NT(I)))/R
      GO TO 40
   30 PWFT(I)=PWF(I)
   40 ATD(I)=2.*CRF(LIM)*(NT(I)-PWFT(I))/(NT(I)*(NT(I)+1.)*R)
      IF (ITST.EQ.0) GO TO 50
      AAD(I)=(ATD(I)-1./N(I))*(CT/(1.-CT))
      AITC(I)=CRF(I)*CITC/((1.+R)*(1.-CT))
      GO TO 60
   50 AAD(I)=(ATD(I)-1./N(I))*(1.-CT*RD*CD/R)*(CT/(1.-CT))
      AITC(I)=(CITC/(1.-CT))*(CRF(I)/(1.+R)-CT*RD*CD*(CRF(I)/(1+R)-1./N(
     +I))/R)
   60 FCR(I)=CRF(I)+AIT(I)-AAD(I)-AITC(I)+CPI
      DO 100 I=1,M
      IF (N(I).LT.LIFE) GO TO 70
      CIR(I)=1.
      GO TO 90
   70 A=LIFE
      B=N(I)
```

```
      NR(I)=A/B
      IF ((LIFE/N(I))*N(I).EQ.LIFE) NR(I)=NR(I)-1
      SUM=0.
      IUP=NR(I)
      DO 80 J=1,IUP
 80   SUM=SUM+(1.+CE(I))/(1.+R)**(J*N(I))
      CIR(I)=(CRF(LIM)/CRF(I))*(FCR(I)/FCR(LIM))*(1.+SUM)
 90   RF(I)=(1.+CF(I))/(1.+R)
      FLF(I)=CRF(LIM)*(RF(I)*(1.-RF(I)**LIFE)/(1.-RF(I)))
100   CONTINUE
      EF=(1.+CO)/(1.+R)
      VOM=CRF(M+1)*(EF*(1.-EF**LIFE)/(1.-EF))
      SUM1=NBKUP*CC(2)
      COML=0.
      FCL=0.
      DO 110 I=1,M
      SUM1=SUM1+CC(I)*CIR(I)
      COML=COML+OM(I)
110   FCL=FCL+(FUEL(I)+FMIN)*FC(I)*FLF(I)
      COML=COML*VOM
      ECC=FCR(LIM)*SUM1
      TTLC=ECC+COML+FCL
      BBC=TTLC/XKWH
      RETURN
      END
```

```
C***************************************************************************
C        SUBROUTINE TO SIMULATE THE PERFORMANCE OF A SPECIFIED            *
C        PV+DIESEL SYSTEM.                                                 *
C***************************************************************************
      SUBROUTINE SIMULA (PVSIZ,CCOEF,DCOEF,PVEFF,ETABB,BATDPT,DDISCH,IEN
     +OFF,IONNPT,BATSZZ,RLL,SIZZ,UPLIM,ALOWL,GALS,RUNT,TOTDEM,SOLO,IPL,I
     +PS,PCTTIM,PCTDEM,TOTDIS,TOTDEF,TOTPV,IONOPT,IENBUP)
      DIMENSION
     +    DEMAND(24),    RLL(5),        SUN(24)
      REAL
     +    KNT
      COMMON /CHARG/
     +    BATCHG,        BATSIZ,        CHGLIM,        CHRG,
     +    ETAB,          SUMDUM
      COMMON /FUELR/
     +    DR(5),         RR(5),         SIZE
      ETAB=ETABB
      DO 10 I=1,5
   10 RR(I)=RLL(I)
      DO 20 I=1,4
   20 DR(I)=(RR(I+1)-RR(I))*4.
      SIZE=SIZZ
      BATSIZ=BATSZZ
      DISLIM=DCOEF*BATSIZ
      CHGLIM=CCOEF*BATSIZ
      BATLL=(1.-DDISCH)*BATSIZ
      BATCHG=BATDPT*BATSIZ/100.
      REWIND 7
      REWIND 9
      TOTDEM=0.
      TOTDEF=0.
      TOTDIS=0.
      TOTPV=0.
      TOTDUM=0.
      RUNT=0.
      GALS=0.
      KNT=0
      REWIND 10
      IENON=0
      DO 150 I=1,365
      READ (7,160) SUN
      READ (9,160) DEMAND
      SUMPV=0.
      SUMDIS=0.
      SUMDEM=0.
      SUMDUM=0.
      SUMDEF=0.
      DO 140 K=1,24
      DEFF=0.
      PV=SUN(K)*PVSIZ*PVEFF
      SUMPV=SUMPV+PV
      SUMDEM=SUMDEM+DEMAND(K)
      DIFF=DEMAND(K)-PV
      IF (DIFF.GT.0.) GO TO 30
```

```
C*****************************************************************************
C         PROGRAM COMES HERE WHEN PV SATISFIES ALL THE DEMAND               *
C*****************************************************************************
      IENON=0
      CHRG=PV-DEMAND(K)
      CALL CHARGE
      GO TO 140
C*****************************************************************************
C         PROGRAM COMES HERE WHEN PV CAN NOT SATISFY THE DEMAND             *
C*****************************************************************************
   30 ADD=0.
      DF=DIFF
      IF (BATCHG.GT.BATLL) GO TO 40
C*****************************************************************************
C         PROGRAM COMES HERE WHEN BATTERY CHARGE IS VERY LOW.               *
C*****************************************************************************
      ENG=MAX(0.,(UPLIM-DIFF))
      ADD=MIN((BATSIZ-BATCHG),CHGLIM,ENG)
      IF (IENBUP.EQ.1) GO TO 60
      GO TO 50
C*****************************************************************************
C         PROGRAM COMES HERE WHEN BATTERIES ARE USED TO SATISFY THE         *
C         DEMAND. AMOUNT OF DISCHARGE IS LIMITED BY BATTERY'S LOW LIMIT     *
C         (BATLL) OR THE ALLOWABLE RATE OF DISCHARGE.                       *
C*****************************************************************************
   40 XLIM1=DISLIM
      XLIM2=BATCHG-BATLL
      XLIM3=DIFF
      DSCH=MIN(XLIM1,XLIM2,XLIM3)
      BATCHG=BATCHG-DSCH
      DIFF=DIFF-DSCH
      DF=DIFF
C*****************************************************************************
C         IF DIFF>0, ENGINE MAY BE TURNED ON SINCE BATTERY ALONE CAN NOT*
C         SATISFY THE DEMAND.                                               *
C*****************************************************************************
      IF (DIFF.GT.0..AND.IENBUP.EQ.1) GO TO 60
      IF (DIFF.GT.0.) GO TO 50
      IENON=0
      GO TO 140
   50 IF (SUN(K).GT.SOLO) GO TO 130
C*****************************************************************************
C         PROGRAM COMES HERE WHEN THE GENERATOR IS USED TO SATISFY THE      *
C         REMAINING DEMAND (DIFF).                                          *
C*****************************************************************************
   60 IADD=1
      IF (UPLIM.GE.DIFF) GO TO 80
      IF (IENON.EQ.1) GO TO 70
C*****************************************************************************
C         THE ENGINE IS PENALIZED WHEN IT IS STARTED                        *
C*****************************************************************************
      IADD=IADD+IPS
      IENON=1
   70 FUEL=CONS(UPLIM)
```

```
      GALS=GALS+FUEL
      RUNT=RUNT+IADD
      DEFF=DIFF-UPLIM
      SUMDIS=SUMDIS+UPLIM
      SUMDEF=SUMDEF+DEFF
      KNT=KNT+1
      GO TO 140
   80 IF (IONNPT.EQ.0) GO TO 90
C***********************************************************************
C        USE THE GENERATOR TO CHARGE THE BATTERIES.                    *
C***********************************************************************
      DIFF=DIFF+ADD
   90 IF (DIFF.GE.ALOWL) GO TO 100
      IF (IONOPT.EQ.0) GO TO 120
C***********************************************************************
C        RUN THE GENERATOR EVEN IF THE LOAD IS LOW.                    *
C***********************************************************************
      IADD=IADD+IPL
  100 IF (IENNON.EQ.1) GO TO 110
C***********************************************************************
C        START THE GENERATOR.                                          *
C***********************************************************************
      IADD=IADD+IPS
      IENON=1
  110 FUEL=CONS(DIFF)
      SUMDIS=SUMDIS+DIFF
      GALS=GALS+FUEL
      RUNT=RUNT+IADD
      CHRG=ADD*IONNPT
C***********************************************************************
C        GENERATED ENERGY IN EXCESS OF DEMAND IS USED IN CHARGING      *
C        THE BATTERY.                                                  *
C***********************************************************************
      CALL CHARGE
      GO TO 140
C***********************************************************************
C        PROGRAM COMES HERE WHEN UNSATISFIED DEMAND IS LOW AND         *
C        THE GENERATOR IS NOT TO BE RUN.                               *
C***********************************************************************
  120 DIFF=DF
  130 IENON=0
      DEFF=DIFF
      SUMDEF=SUMDEF+DEFF
      KNT=KNT+1
  140 CONTINUE
      TOTDIS=TOTDIS+SUMDIS
      TOTDEM=TOTDEM+SUMDEM
      TOTDEF=TOTDEF+SUMDEF
      TOTPV=TOTPV+SUMPV
  150 CONTINUE
      PCTTIM=(8760.-KNT)/8760.*100.
      PCTDEM=(TOTDEM-TOTDEF)/TOTDEM*100.
      IF (SIZE.LT.1.E-6) RUNT=0.
      RETURN
```

```
160 FORMAT (4X,24(1X,F4.2))
    END
```

```
C*********************************************************************
C        SUBROUTINE TO SIMULATE THE PERFORMANCE OF A SPECIFIED       *
C        PV+DIESEL SYSTEM.                                            *
C                                                                     *
C        THIS PROGRAM HAS BEEN MODIFIED TO USE PV ENERGY FIRST        *
C        THEN GENERATOR AND FINALLY BATTERY. THUS BATTERY ACTS AS     *
C        BACK-UP. OTHERWISE BATTERY IS DISCHARGED AT NIGHT AND        *
C        GENERATOR AND PV ARE INADEQUATE FOR DEMAND DURING LOW PV     *
C        PERIODS.                                                     *
C*********************************************************************
      SUBROUTINE SIML1 (PVSIZ,CCOEF,DCOEF,PVEFF,ETABB,BATDPT,DDISCH,IENO
     +FF,IONNPT,BATSZZ,RLL,SIZZ,UPLIM,ALOWL,GALS,RUNT,TOTDEM,SOLO,IPL,IP
     +S,PCTTIM,PCTDEM,TOTDIS,TOTDEF,TOTPV,IONOPT,IENBUP)
      DIMENSION
     +    DEMAND(24),     RLL(5),        SUN(24)
      REAL
     +    KNT
      COMMON /CHARG/
     +    BATCHG,         BATSIZ,        CHGLIM,         CHRG,
     +    ETAB,           SUMDUM
      COMMON /FUELR/
     +    DR(5),          RR(5),         SIZE
      ETAB=ETABB
      DO 10 I=1,5
   10 RR(I)=RLL(I)
      DO 20 I=1,4
   20 DR(I)=(RR(I+1)-RR(I))*4.
      SIZE=SIZZ
      BATSIZ=BATSZZ
      DISLIM=DCOEF*BATSIZ
      CHGLIM=CCOEF*BATSIZ
      BATLL=(1.-DDISCH)*BATSIZ
      BATCHG=BATDPT*BATSIZ/100.
      REWIND 7
      REWIND 9
      TOTDEM=0.
      TOTDEF=0.
      TOTDIS=0.
      TOTPV=0.
      TOTDUM=0.
      RUNT=0.
      GALS=0.
      KNT=0
      REWIND 10
      IENON=0
      DO 140 I=1,365
      READ (7,150) SUN
      READ (9,150) DEMAND
      SUMPV=0.
      SUMDIS=0.
      SUMDEM=0.
      SUMDUM=0.
      SUMDEF=0.
      DO 130 K=1,24
```

```
      DEFF=0.
      PV=SUN(K)*PVSIZ*PVEFF
      SUMPV=SUMPV+PV
      SUMDEM=SUMDEM+DEMAND(K)
      DIFF=DEMAND(K)-PV
      IF (DIFF.GT.0.) GO TO 30
C************************************************************************
C        PROGRAM COMES HERE WHEN PV SATISFIES ALL THE DEMAND            *
C************************************************************************
      IENON=0
      CHRG=PV-DEMAND(K)
      CALL CHARGE
      GO TO 130
C************************************************************************
C        PROGRAM COMES HERE WHEN PV CAN NOT SATISFY THE DEMAND          *
C************************************************************************
   30 ADD=0.
      DF=DIFF
      IF (BATCHG.GT.BATLL) GO TO 40
C************************************************************************
C        IF BATTERY CHARGE IS VERY LOW, POSSIBLY THE GENERATOR MAY      *
C        BE USED TO CHARGE THE BATTERIES. "ENG" IS THE AMOUNT OF        *
C        CHARGE THAT CAN BE PROVIDED BY THE GENERATOR AND "ADD"         *
C        IS THE AMOUNT OF CHARGE ACCEPTABLE BY THE BATTERIES.           *
C************************************************************************
      ENG=MAX(0.,(UPLIM-DIFF))
      ADD=MIN((BATSIZ-BATCHG),CHGLIM,ENG)
   40 IF (IENBUP.EQ.1) GO TO 50
      IF (SUN(K).GT.SOLO) GO TO 120
C************************************************************************
C        WHEN THE PROGRAM COMES HERE, THE GENERATOR WILL HELP           *
C        SATISFY THE DEMAND. IF THE POTENTIAL GENERATOR OUTPUT IS       *
C        GREATER THAN UNSATISFIED DEMAND, CHECK TO SEE IF THE EXTRA     *
C        OUTPUT CAN BE USED TO CHARGE THE BATTERY (SEE STATEMENT 70).   *
C        AT THIS TIME, IF THE GENERATOR IS NOT ON, TURN IT ON AND       *
C        PENALIZE FOR START-UP.                                         *
C************************************************************************
   50 IADD=1
      IF (UPLIM.GE.DIFF) GO TO 70
      IF (IENON.EQ.1) GO TO 60
      IADD=IADD+IPS
      IENON=1
   60 FUEL=CONS(UPLIM)
      GALS=GALS+FUEL
      RUNT=RUNT+IADD
      DIFF=DIFF-UPLIM
      SUMDIS=SUMDIS+UPLIM
      GO TO 120
C************************************************************************
C        PROGRAM COMES HERE WHEN THE GENERATOR IS USED TO SATISFY       *
C        THE DEMAND AND CHARGE THE BATTERIES.                           *
C************************************************************************
   70 IF (IONNPT.EQ.0) GO TO 80
      DIFF=DIFF+ADD
```

```
   80 IF (DIFF.GE.ALOWL) GO TO 90
      IF (IONOPT.EQ.0) GO TO 110
      IADD=IADD+IPL
   90 IF (IENNON.EQ.1) GO TO 100
      IADD=IADD+IPS
      IENON=1
  100 FUEL=CONS(DIFF)
      SUMDIS=SUMDIS+DIFF
      GALS=GALS+FUEL
      RUNT=RUNT+IADD
      CHRG=ADD*IONNPT
      CALL CHARGE
      GO TO 130
C***********************************************************************
C        PROGRAM COMES HERE WHEN THE GENERATOR IS NOT USED WHEN        *
C        THE UNSATISFIED DEMAND IS BELOW A PRE-SET LIMIT (ALOWL).      *
C        BATTERIES DISCHARGE TO SATISFY THE DEMAND. "KNT" COUNTS       *
C        THE NUMBER OF HOURS DEMAND CAN NOT BE SATISFIED.              *
C***********************************************************************
  110 DIFF=DF
  120 XLIM1=DISLIM
      XLIM2=BATCHG-BATLL
      XLIM3=DIFF
      DSCH=MIN(XLIM1,XLIM2,XLIM3)
      BATCHG=BATCHG-DSCH
      DEFF=DIFF-DSCH
      SUMDEF=SUMDEF+DEFF
      IF (DEFF.GT.0.) KNT=KNT+1
  130 CONTINUE
      TOTDIS=TOTDIS+SUMDIS
      TOTDEM=TOTDEM+SUMDEM
      TOTDEF=TOTDEF+SUMDEF
      TOTPV=TOTPV+SUMPV
  140 CONTINUE
      PCTTIM=(8760.-KNT)/8760.*100.
      PCTDEM=(TOTDEM-TOTDEF)/TOTDEM*100.
      IF (SIZE.LT.1.E-6) RUNT=0.
      RETURN
  150 FORMAT (4X,24(1X,F4.2))
      END
```

APPENDIX B

INPUT DATA FOR SECTION 4.0 ANALYSES

PV HYBRID SYSTEM RESOURCE INPUT DATA

1. SOLAR INSOLATION INPUT DATA

- LOCATION - TUCSON, AZ.
- LATITUDE - 32.11°
- GROUND REFLECTANCE (RHO) - 0.05
- ARRAY TILT ANGLE - 32.11
- CLEARNESS INDEXES:

J	F	M	A	M	J	J	A	S	O	N	D
.667	.667	.737	.758	.768	.711	.647	.651	.720	.681	.690	.690

2. WIND SPEED INPUT DATA

- HUB HEIGHT - 10 meters

(i) WIND SPEED WINTER PEAKING, NIGHT PEAKING

- HOURLY MEAN WIND SPEED (M/S):

HOUR	1	12	23
SPEED	10	5	9

- MONTHLY MEAN WIND SPEED (M/S):

J	F	M	A	M	J	J	A	S	O	N	D
10	9	8	7	6	5	4	5	6	7	8	9

(ii) WIND SPEED SUMMER PEAKING, NIGHT PEAKING

- HOURLY MEAN WIND SPEED (M/S):

HOUR	1	12	23
SPEED	10	5	9

- MONTHLY MEAN WIND SPEED (M/S):

J	F	M	A	M	J	J	A	S	O	N	D
4	5	6	7	8	9	10	9	8	7	6	5

(iii) WIND SPEED WINTER PEAKING, NIGHT PEAKING (HIGH SPEEDS)

- HOURLY MEAN WIND SPEED (M/S):

HOUR	1	12	23
SPEED	15	5	15

- MONTHLY MEAN WIND SPEED (M/S):

J	F	M	A	M	J	J	A	S	O	N	D
16	14	14	12	12	10	8	8	10	12	14	16

(iv) WIND SPEED WINTER PEAKING, DAY PEAKING

- HOURLY MEAN WIND SPEED (M/S):

HOUR	1	12	23
SPEED	5	10	4

- MONTHLY MEAN WIND SPEED (M/S):

J	F	M	A	M	J	J	A	S	O	N	D
10	9	8	7	6	5	4	5	6	7	8	9

(v) WIND SPEED WINTER PEAKING, NIGHT PEAKING (MEDIUM SPEEDS)

- HOURLY MEAN WIND SPEED (M/S):

HOUR	1	12	23
SPEED	15	5	15

- MONTHLY MEAN WIND SPEED (M/S)

J	F	M	A	M	J	J	A	S	O	N	D
10	9	8	7	6	5	5	6	7	8	9	10

3) <u>WATER FLOW INPUT DATA</u>

- DESIGN HEAD - 10 meters

(i) CONSTANT SEASONAL WATER FLOW (100 and 1000 kwh/day)

- MONTHLY WATER FLOW (M^3/sec.)

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
100 kwh/day	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
1000 kwh/day	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4

(ii) ONE MONTH DROUGHT (100 and 1000 kwh/day)

- MONTHLY WATER FLOW (M^3/Sec.):

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
100 kwh/day	0.14	0.14	0.14	0.14	0.14	0	0.14	0.14	0.14	0.14	0.14	C-14
1000 kwh/day	1.4	1.4	1.4	1.4	1.4	0	1.4	1.4	1.4	1.4	1.4	1.4

(iii) SIMILAR DISTRIBUTION FOR PROLONGED PERIODS OF DROUGHT

PV HYBRID SYSTEMS EQUIPMENT INPUT DATA

INPUT DATA FOR PV ARRAY

PV ARRAY COST ($/KWP)	PV EFFICIENCY (%)	PV O&M (% OF CAPITAL COST)	PV LIFE (YRS)	PV COST ESCALATION (%)
$5000 $3000	10	1	20	0

INPUT DATA FOR BATTERY

MAXIMUM BATTERY DISCHARGE RATE (%)	MAXIMUM BATTERY CHARGE RATE (%)	BATTERY DEPTH OF DISCHARGE (%)	BATTERY EFFICIENCY (%)	BATTERY COST ($/KWH)	BATTERY O&M (% OF) CAPITAL COST	BATTERY LIFE (YRS)	BATTERY COST ESCALATION (%)
25	25	70	85	125/150	1	10	0

INPUT DATA FOR WIND GENERATORS

WIND GENERATOR SIZE (KW)	CUT IN SPEED (M/S)	RATED SPEED (M/S)	CUT OUT SPEED (M/S)	WIND MACHINE COST ($)	WIND MACHINE O&M (% OF CAPITAL COST)	WIND SPEED MEASUREMENT HEIGHT (M)	HUB HEIGHT (M)	WIND MACHINE LIFE (YRS)	WIND MACHINE COST ESCALATION (%)
1.2	4	11	40	6000	2.5	10	10	20	0
1.8	4	11	40	8000	2.5	10	10	20	0
4.0	4	11	40	12000	2.5	10	10	20	0
7.5	4	11	40	18750	2.5	10	10	20	0
10	4	11	40	17000	2.5	10	10	20	0
15	4	11	40	19500	2.5	10	10	20	0
25	4	11	40	25000	2.5	10	10	20	0
50	5.5	11	35	50000	2.5	10	10	20	0
100	5.5	11	25	100000	2.5	10	10	20	0
150	5.5	11	25	150000	2.5	10	10	20	0
200	5.5	11	25	200000	2.5	10	10	20	0
300	5.5	11	25	300000	2.5	10	10	20	0
500	5.5	11	25	500000	2.5	10	10	20	0

INPUT DATA FOR HYDRO TURBINES

HYDRO TURBINE SIZE (KW)	DESIGN HEAD (M)	HYDRO TURBINE COST ($)	HYDRO TURBINE O&M (% OF CAPITAL COST)	HYDRO TURBINE LIFE (YRS)	HYDRO TURBINE COST ESCALATION (%)	EFFICIENCY AND REQUIRED FLOW RATE (%, M^3/S)									
						FLOW 1	EFF 1	FLOW 2	EFF 2	FLOW 3	EFF 3	FLOW 4	EFF 4	FLOW 5	EFF 5
10	10	30000	1	20	0	0.012	64	.024	73	.036	75	.06	75	.12	75
100	10		1	20	0										

INPUT DATA FOR GASOLINE AND DIESEL ENGINES

DIESEL ENGINE SIZE (KW)	DIESEL ENGINE COST ($)	DIESEL ENGINE O&M $/hr OP	DIESEL ENGINE LIFE (YRS)	DIESEL ENGINE COST ESCALATION (%)	MINIMUM OPERATING CAPACITY (%)	MAXIMUM OPERATING CAPACITY (%)	NOMINAL OPERATING CAPACITY FACTOR (%)	FUEL CONSUMPTION AT DIFFERENT CAPACITY LEVELS (GAL/HR)				
								IDLE	25%	50%	75%	100%
0.3*	400	0.20	15	0	50	80	60	0.05	0.07	0.09	.11	.13
0.4*	470	0.20	15	0	50	80	60	0.05	0.07	0.09	.11	.13
0.8*	600	0.25	15	0	50	80	60	.1	.14	.18	.22	.26
3.0	3975	0.26	20	0	50	80	60	.16	.21	.26	.3	.34
4.0	4500	0.28	20	0	50	80	60	.2	.26	.32	.33	.44
6.0	5525	0.32	20	0	50	80	60	.27	.35	.43	.53	.64
9.0	6350	0.35	20	0	50	80	60	.33	.49	.58	.71	.85
30.0	10000	0.49	20	0	50	80	60	.6	1.2	1.8	2.4	3.1
60.0	15310	0.71	20	0	50	80	60	1.2	2.0	2.8	3.7	4.8
75.0	17230	0.90	20	0	50	80	60	1.6	2.5	3.4	4.6	5.8

INPUT DATA FOR FUEL CELL

FUEL CELL SIZE (KW)	FUEL CELL COST ($)	FUEL CELL O&M ($/H.O.P.)	FUEL CELL LIFE (YRS)	FUEL CELL COST ESCALATION (%)	MINUMUM OPERATING CAPACITY (%)	MAXIMUM OPERATING CAPACITY (%)	NOMINAL OPERATING CAPACITY FACTOR (%)	PROPANE EQUIV. CONSUMPTION (LB/HR) AT DIFFERENT CAPACITY LEVELS:				
								IDLE	25%	50%	75%	100%
3	5700	0.01	5	0	25	100	90	.31	1.26	1.35	1.26	1.24
6	11400	0.04	5	0	25	100	90	.62	2.49	2.52	2.49	2.48

INPUT DATA FOR CCVT ENGINES

CCVT ENGINE SIZE (KW)	CCVT ENGINE COST ($)	CCVT ENGINE O&M ($/hr op.)	CCVT ENGINE LIFE (YRS)	CCVT ENGINE COST ESCALATION (%)	MINIMUM OPERATION CAPACITY (%)	MAXIMUM OPERATION CAPACITY (%)	NOMINAL OPERATION CAPACITY FACTOR (%)	PROPANE CONSUMPTION (LB/HR) AT DIFFERENT CAPACITY LEVELS:					
								IDLE	25%	50%	75%	100%	CONSTANT IDLE LB/YR
0.2	18000	0	20	0	0	100	100	0.7	0.7	0.7	0.7	0.7	468

PV HYBRID SYSTEM MISCELLANEOUS INPUT DATA

(i) BALANCE OF SYSTEM COSTS

- PV BALANCE OF SYSTEM COST - $1000/kWp and $600/kWp
- DIESEL BALANCE OF SYSTEMS COST - $700/kW + BACKUP ENGINE
- FUEL CELL BALANCE OF SYSTEM COST - 0
- CCVT BALANCE OF SYSTEM COST - 0
- WIND BALANCE OF SYSTEM COST - 0
- HYDRO BALANCE OF SYSTEM COST - $2300/kW
- BATTERY (HOUSING) BALANCE OF SYSTEM COST - $17/kWh

(ii) MISCELLANEOUS COSTS

- INVERTER AND CONTROL EQUIPMENT
  (a) $10,000 FOR 100 kWh/DAY DEMAND
  (b) $75,000 FOR 1000 kWh/DAY DEMAND
- WIRING COST
  (a) $500 FOR 10 kWh/DAY DEMAND
  (b) $2000 FOR 100 kWh/DAY DEMAND
  (c) $20,000 FOR 1000 kWh/DAY DEMAND
- FUEL COST
  (a) DIESEL - $2/GAL
  (b) PROPANE - $0.5/lb
- DEBT RATIO - 1.0
- DEBT COST - 0.1

(iii) MISCELLANEOUS DATA

- PROJECT LIFE - 20 YEARS

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16. Abstract

This report documents the work done in developing designs of photovoltaic hybrid power systems for remote, stand-alone applications which require 10-1000 kWh/day of electrical energy. Section 1.0 of the report outlines the objectives of the study. Section 2.0 documents the preliminary evaluation conducted to select the candidate syst for a more detailed analysis. Application time frame is 1988-93. Hybrid systems selec were PV/wind, PV/diesel and gasoline generators, PV/hydro, PV/fuel cell and PV/closed cycle vapor turbogenerators. Section 3.0 describes the stochastic computer models developed to conduct hourly performance simulations. The simulations generate the optimal system configurations, levelized busbar costs and percent availability of electric power. Section 4.0 presents the results of the simulation runs which identii PV/diesel, PV/wind and PV/fuel cells as the most promising applications for more detailed design and evaluation. Section 5.0 provides detailed conceptual designs of th diesel, wind and fuel cell hybrid systems. Section 6.0 outlines additional development work that needs to be conducted to improve the cost, performance and reliability of the power systems. Source code listings of the computer models are in Appendix A. Appendi describes the input data used for the analyses in Section 4.0.

17. Key Words (Suggested by Author(s))
Photovoltaics, wind, fuel cells, diesel and gasoline generator sets, stand-alone hybrid power systems, simulation modeling, conceptual designs

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